Technical Report **1746**
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Behavioral Response of Blue Whales to Active Signals

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ADMINISTRATIVE INFORMATION

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EXECUTIVE SUMMARY

The effects of low-frequency sound on marine mammals (particularly the baleen whales) are not well understood. Although baleen whales are known to produce low-frequency sounds, very little is known about their auditory sensitivity. This analysis studied the behavior of blue whales in the vicinity of a loud, low-frequency source by evaluating an available data set recorded during a Low Frequency Active (LFA) experiment. The received source levels at the whales were estimated from the known source levels and a Parabolic Equation (PE) propagation model.

Element level acoustic data collected with a high-gain towed array during the Magellan II sea test conducted off the coast of California contained blue and finback whale detections. An extended set of data containing numerous detections of blue and finback whales was spectrally processed to determine the frequency content and repetition rates of their vocalizations. Subarray beamforming was used to cross-fix the whale positions and track their movement relative to the active source. The effects of active source transmissions on blue whale vocalization patterns and on their movement relative to the source were analyzed.

Estimated received source levels at the whales of 70 to 85 dB below full transmit power did not appear to alter the vocalization patterns of the blue whales as determined by analysis of the repetition rates, frequency characteristics, and durations of the whale vocalizations before, during, and after active transmissions. In addition, several blue whales exhibited a well-documented vocalization pattern consisting of alternating trills and chirps that compared favorably to the vocalization patterns of other blue whales recorded when an active source was not transmitting. Two blue whales were tracked intermittently over a 2.5-hour interval during which there were 18 active transmissions or pings. The ranges of both whales from the source varied during this interval but did not show a tendency towards increasing range from the source over time. Further research as to the effects (both behavioral and physiological) of acoustic energy on marine mammals is needed. This research would enable a sound-level threshold for marine mammals to be determined in the frequency band of interest.

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1. INTRODUCTION

Decades of whaling significantly reduced the population of some baleen whales (mysticetes) to levels that threaten their existence. In the early 1970s, the United States declared its intent to impose severe limitations on the killing or harassment of many marine mammals with passage of the Marine Mammals Protection Act (MMPA) of 1972 and the Endangered Species Act (ESA) of 1973. International reaction to the effects of whaling resulted in a moratorium on commercial whaling in 1986.

In the early 1990s when defense budgets were being cut and the cost of using wide-scale resources for civilian scientific research was escalating, the U.S. Navy, began looking at other cost effective methods to maintain operational capabilities and continue scientific research. One result was the establishment of DoD's Dual Use Initiative. In November 1992, Space and Naval Warfare Systems Command (SPAWAR) and Commander Undersea Surveillance (CUS) jointly initiated Whales '93, an innovative scientific dual use program using existing DoD assets for performing fundamental environmental research. Using information collected by the U.S. Navy's Integrated Undersea Surveillance System (IUSS) and its network of underwater hydrophones, the Whales '93 program sought to catalog the acoustic signals from large marine cetaceans to determine their spatial and temporal distributions in the deep water environment.

At the same time, the scientific community was conducting various studies in earthquake monitoring, ozone depletion, and climate research. One of the more publicized of these projects is the Acoustic Thermometry of Ocean Climate (ATOC), an international 30-month "proof of concept" project to monitor deep ocean temperatures that may yield a better understanding of the overall effect of global warming. It is a follow-on to the Heard Island Feasibility Test (HIFT) conducted in January 1991 off the coast of Heard Island, Australia (Bowles et al., 1994). Its goal was to assess the feasibility of acoustic tomography for long-range monitoring of ocean temperatures. Known as the "sound heard around the world", hydrophones near Bermuda received the sound 3.7 hours later.

Because of the worldwide publicity for the current ATOC project, concerns were voiced regarding the effects of man-made sound on marine mammals protected under the MMPA and the ESA. Since whales and dolphins appear to use sound in feeding, navigation, and communications, the issue is whether man-made sounds have any deleterious physical or behavioral impact on these animals. However, the knowledge base that exists on this issue is extremely limited and until more research is done, the impact is unknown. A continuing debate over ATOC's possible impact on marine mammals versus the benefits of additional global warming information has risen. Much of the marine mammal concern stemmed from questions raised in February and March 1994, and there was also concern expressed by the National Marine Sanctuaries Program (NMSP) as to the proposed location of an ATOC source in the Monterey Bay National Marine Sanctuary (MBNMS). The primary responsibility for the conservation of whales and dolphins is delegated by the Secretary of Commerce to the National Marine Fisheries Service (NMFS) within the National Oceanic and Atmospheric

Administration (NOAA). An independent Marine Mammal Commission (MMC) was established by Title II of the MMPA to make recommendations to NMFS to ensure that the intent and provisions of the Act are met.

In October 1991, NMFS and the Office of Naval Research (ONR) held a workshop on the possible effects of low-frequency, high-intensity sound on marine mammals. Following the workshop, ONR funded a National Research Council (NRC) investigation of current knowledge and research needs in this area. Released in March 1994, the NRC report concluded that there was insufficient scientific data to determine the possible effects of low-frequency sound on marine mammals (NRC, 1994). Marine mammal hearing tests have been limited to captive species, therefore, relatively little or nothing is known about the hearing abilities of baleen whales as well as other marine mammals. Baleen whales are believed to be more sensitive to low-frequency (below 100 Hz) sound because their vocalizations occur in that frequency range. The NRC report emphasized the need for increased and better studies on wild marine mammal behavior and marine mammal audition, and a review of the MMPA scientific research permitting process.

Consequently, the U.S. Navy has taken the initiative to monitor whales and other ocean mammal life when its projects involve underwater acoustics. Planning and execution of mitigative measures are now an integral part of test planning to avoid adverse acoustic impact on marine wildlife. These measures include: 1) observing and evaluating behavior of animals in the test area; 2) suspending testing under conditions of unusual animal behavior or sighting/localizing an animal within 1 nautical mile (nm) of the sound source; 3) conducting environmental area assessment studies including characterizing the acoustic environment and establishing marine animal population densities, species distribution, and behavior; and 4) conducting species-specific studies to include vocalization behavior and source level. During Magellan II, on which this report is focused, mitigative measures were taken and data were acquired primarily on two mysticete species where there were numerous close-in detections: blue and finback whales.

1.1 TEST OVERVIEW

In 1993 and 1994, the Magellan Sea Tests consisted of at-sea exercises designed to test new and existing systems and tools and to demonstrate their usefulness in Fleet (antisubmarine warfare) ASW operations. SPAWAR PD 80 managed these sea tests through PMW 182. SPAWAR had tasked the Naval Command, Control and Ocean Surveillance Center RDTE Division (NRaD), code D71, with planning the Magellan Sea Test Series, conducting the at-sea tests, initial data analysis, and generation of the quick-look reports. The intent of the Magellan sea tests was not to replace individual system test and evaluation, but to maximize the cost effectiveness of T&E and to develop a mobile, sustainable ASW capability for use in protection of expeditionary forces responding to heightened tensions or regional conflicts on short notice. Magellan I took place in the Mediterranean Sea in 1993, and Magellan II occurred off the coast of California in 1994.

Magellan I and II incorporated a number of R&D surveillance tools, existing surveillance systems, and fleet assets. The exact composition of assets depended upon the geopolitical features of the area. In both tests, however, the objectives were the same. The test team objectives were to resolve critical active acoustic, passive acoustic, non-acoustic, and communication and command issues relating to deep, transitional, and shallow water operations.

Magellan II, which took place in the northeast Pacific Ocean off the coast of California, is the focus of this report. The Magellan II schedule is shown in table 1 and the test operating areas (OPAREAs) are shown in figure 1. During Magellan II, there were numerous close-in detections of blue and finback whales during the Shakedown Test (26-27 July 1994); Segment 1 (3-18 August 1994); and Segment 2 (24 August to 2 September 1994) components. Using multi-sensor data collected at sea during Magellan II, track correlations were performed with active transmissions to try to assess whale response to active signals. These data sets provide a unique opportunity to evaluate the effect of low-frequency sound on whales.

Table 1. Magellan II Schedule.

Event	Period	Whale Detections
R/V-1 Shakedown	18-28 Jul 94	26-27 Jul 94
Segment 1 (SOCAL)	3-19 Aug 94	3-18 Aug 94
Segment 2 (NORCAL)	22 Aug - 2 Sep 94	24 Aug - 2 Sep 94

1.2 SOURCES

During Magellan II, the primary source of acoustic transmissions was the SURTASS/Low Frequency Active (LFA) System. The LFA system began development initially as the Active Adjunct Undersea Surveillance (AAUS) Exploratory Development Program. LFA was initially developed to regain a reliable area surveillance capability lost in the mid-1980s to a generation of Soviet nuclear submarines with significantly reduced radiation noise levels. Development in the 1990s has focused on Rest of World (ROW) diesel submarine threats in littoral operating environments. NRaD provided technical guidance in the development of the LFA Technology Demonstration System and directed nine at-sea tests with the system culminating in successful DT-I and OT-I sea tests in 1990. Since then, NRaD has directed several additional sea tests to further characterize LFA performance in a variety of acoustic environments and operational scenarios, the latest being a fleet exercise off the Southern California coast in March 1996. As part of its marine mammal mitigation requirements, LFA

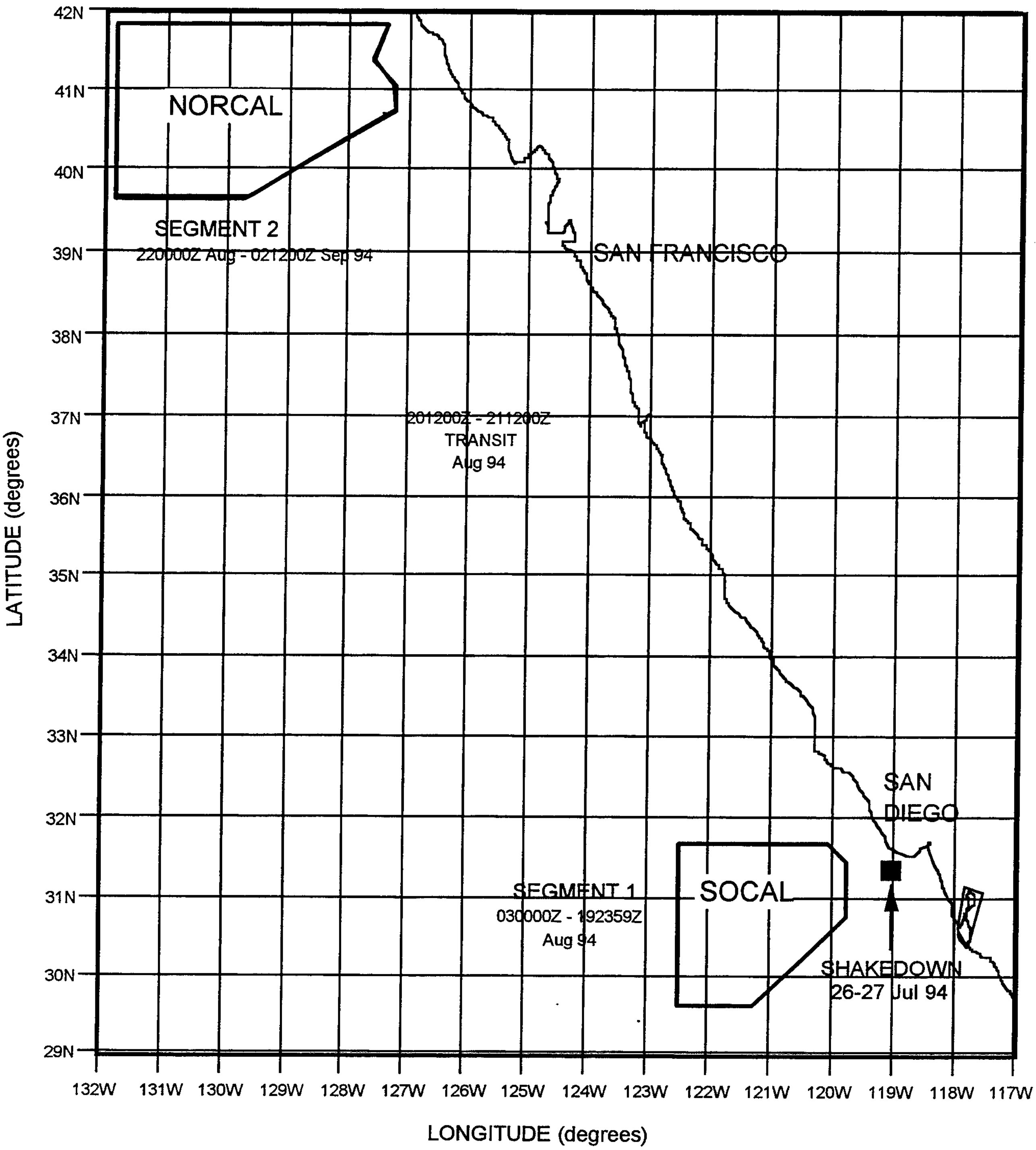

Figure 1. Magellan II operating areas.

transmissions are suspended when any whale activity is detected within 1 nmi of the LFA transmit array or when any other marine animal activity is detected within 1000 yards of the source array.

LFA is an operational undersea surveillance program in which specialized sound pulses are generated by a sound source deployed from a ship, and echo data are acquired by an acoustic passive sensor array also towed by the ship. Computer-generated, beamformed acoustic pulses are transmitted via a vertical array of projectors. Underwater acoustic signals and echoes are then received by a towed horizontal array. These signals are conditioned, filtered, and converted into digital data for beamforming and processing. The LFA shipboard electronic equipment generates and shapes the sound signals to be projected, conditions the received echo data, and processes and displays the information.

The platform used for conducting LFA tests was the Research Vessel (R/V) *Cory Chouest*, a commercial ship on lease to the U.S. Navy. The ship was modified in February 1987, to support LFA and has accommodations for a ship's crew of 12 and a scientific crew of 54.

Two arrays are operated from R/V *Cory Chouest*. The Receive or Horizontal Line Array (HLA) contains receive hydrophones and associated equipment, including amplifiers with harnesses, connectors, and depth, temperature, and heading sensors. The Transmit or Vertical Line Array (VLA) consists of an assemblage of heavy chains and individual transducer elements that are deployed through a center well using the VLA handling system.

The source subsystem develops high power, low-frequency acoustic energy transmission. It also collects data from various sensors that allow the performance and status of the source array to be assessed in real-time.

1.3 MARINE MAMMAL OVERVIEW

During Magellan II, on which this report is focused, detection data on blue and finback whales was collected and processed.

1.3.1 BLUE WHALES

The blue whale *(Balaenoptera musculus)* is distributed in temperate and cold waters worldwide, as indicated in figure 2. The largest animal to ever inhabit this planet, its average length is 82 feet and its weight ranges between 80 and 120 tons. Female blue whales are 3 to 7 feet longer and approximately 10 tons heavier than males. Blue whales reach physical maturity at 15 years and their life expectancy is 35 to 40 years or more. When feeding, blue whales swim at 1 to 3.5 kts and can attain speeds of 21 to 26 kts.

With regards to physical appearance, blue whales are mainly blue-gray in color and have evenly spaced throat grooves that extend from the chin to the navel. The tips and undersides of the flippers are light gray to snow-white and the belly and sides are often flecked with pearl-gray, yellow, or brown markings. The flippers are rarely longer than 8 feet, and the dorsal fin is usually no more than 12 to

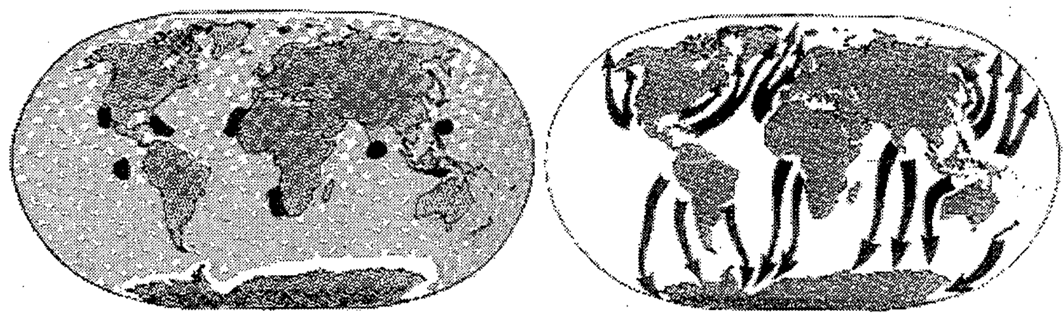

Figure 2. Blue whale breeding areas and migration patterns.

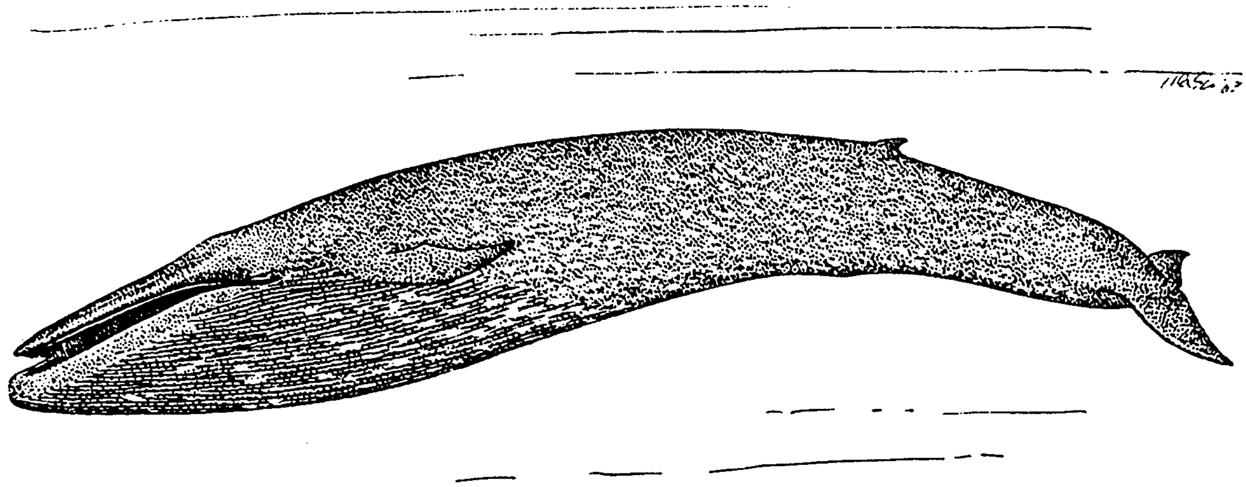

Figure 3. Blue whale (reprinted by permission, Ridgway 1972).

14 inches high, extremely small compared to the total body length. Figure 3 depicts a blue whale. Blue whales produce very-low-frequency sounds with source levels in excess of 188 dB//μPa @ 1m over a 14- to 222-Hz band (Cummings and Thompson, 1971). During Magellan II, blue whale source levels at 17 Hz were estimated to be in the range of 195 dB//μPa @ 1m. These are very high source levels and at 17 Hz are difficult to produce even with man-made sources. Table 2 shows the source levels for various natural and man-made signals. It is noted that the finback whale produces the highest source level of all recorded marine mammals, with vocalizations up to 200 dB//μPa @ 1m over a 20- to 1000-Hz band.

Figure 4 shows the general characteristics of the blue whale vocalizations as documented in McDonald et al. (1995). Figure 5 shows the blue whale vocalizations observed during the Magellan II

Table 2. Natural and man-made source noise comparisons in the 20- to 1000-Hz band

Noise Source	Source Level (dB//μPa @ 1m)	REMARKS
Sea floor volcano eruption	280	Massive steam explosions
Undersea earthquake	272	Magnitude 4.0 on Richter Scale (energy integrated over 50-Hz bandwidth)
Lightning strike on water surface	260	Random events during storms at sea
Airgun array (seismic)	255	Compressed air discharged into piston assembly
Vibroseis (seismic)	230	Seismic profiling through shore-fast ice using hydraulically-driven pads
Sparker (seismic)	221	Electric discharge of a capacitor across two metallic plates
Gas sleeve exploder (seismic)	217	Ignition of gas mixture in plastic sleeve
Water gun (seismic)	217	High-pressure water to solenoid-triggered piston
Boomer (seismic)	212	Electric discharge of a capacitor across two metallic plates
Finback whale	200	Vocalizations: pulses, moans
Container ship	198	Length 274 meters; speed 23 knots
ATOC Source	195	Depth 850 meters; pulse sequence compression used to help mask signal
Humpback whale	190	Fluke and flipper slaps
Super tanker	190	Length 350 meters; speed 20 knots
Bowhead whale	189	Vocalizations: songs
blue whale	188	Vocalizations: low frequency moans
Right whale	187	Vocalizations: pulsive signal
Gray whale	185	Vocalizations: moans
Off shore drill	185	Ref: Motor Vessel Kulluk; oil/gas exploration
Off shore dredge	185	Ref: Motor Vessel Aquarius
Open ocean ambient noise	120	High end of spectrum

sea test. They are nearly identical to those given by McDonald, with the exception of the 10-Hz component that was observed only when a blue whale was relatively close to the array. As far as is known, this source has not been previously observed. Figure 6 shows another vocalization, a powerful sequence of down sweeps from 68 to 17 Hz that is suspected to be associated with blue whales but has not been confirmed.

The known blue whale vocalization consists basically of two parts. Part A is a tonal near 17 Hz, lasting approximately 20 seconds, as shown in figures 4 and 5. In these figures, the y-axis is time and the x-axis is frequency, with a resolution of 0.6 Hz. There is amplitude modulation, and on the spectra, the tones repeated at intervals of approximately 1.5 Hz above 17 Hz. Part A became known as the "trill" by one of the scientists aboard R/V *Cory Chouest* during the Magellan II Segment 1 Sea Test. In the 84 to 98 Hz region the "trill" is fairly strong and provides a good candidate for broadband hydrophone correlation and tracking functions. After the trill (Part A) there is an approximate 15-second gap. After the gap the blue whale emits Part B of the signal. The first part is a 10-Hz tonal that lasts about 10 seconds. This tonal is rarely seen so there appears to be a 25-second gap. After the 10-Hz tonal there is a down swept frequency starting at 19 Hz and sweeping down to 18 Hz in approximately 5 seconds. The 18-Hz tone is maintained for approximately 10 seconds, then it

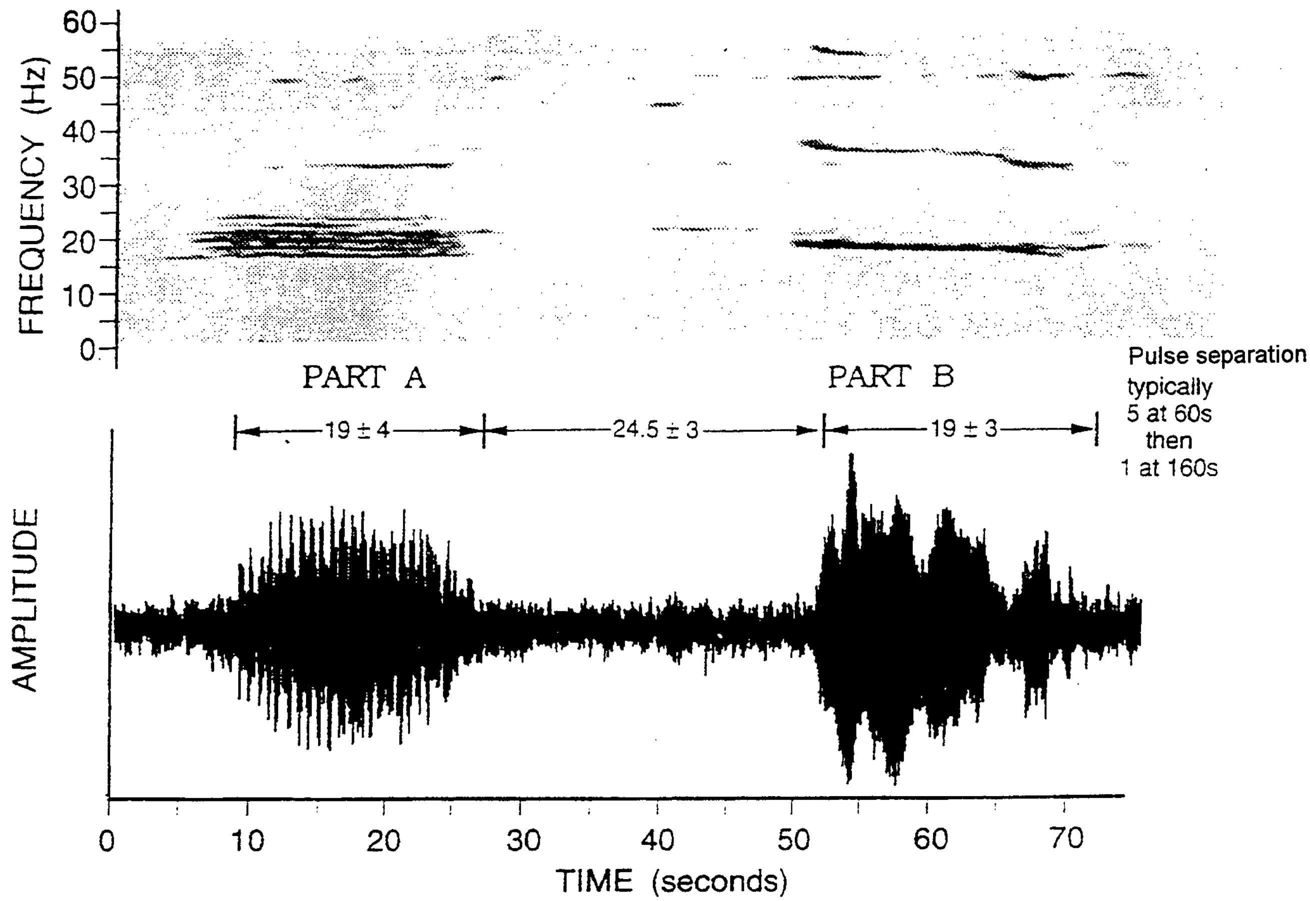

FIGURE 4. Spectrogram and corresponding time series record of a typical blue whale call pair. The spectrogram was made using a filter bandwidth of 1.55 Hz and a time window of 4 seconds. The average duration and standard deviation for each portion of the call pair sequence is shown from one sequence of 132 call pairs. The call is divided into two portions, parts a and b. (reprinted with permission of McDonald)

is swept down to 17 Hz in approximately 5 seconds. When the 10 Hz tonal is included, the Part B vocalization lasts approximately 30 seconds. This pattern of vocalization (Part A, gap, Part B) is repeated quite regularly four or five times and then there is a gap for several minutes (a breathing period perhaps). It is important to understand this pattern so that one may judge more accurately how, if at all, active emissions affect blue whale vocalization patterns. Blue whale "calls" follow a repetitive, structured pattern interrupted only when the whale surfaces to breathe. Blue whale calls are among the most powerful sustained utterances from whales or any other living sound source. The fifth harmonic (with fundamental near 17 Hz) of this vocalization frequency is occasionally observed. In the Navy surveillance community, this biologic sound is referred to as a "comma" due to its resemblance on acoustic displays to that of the punctuation mark. Unfortunately, until 1993, it was thought to have been caused by snapping shrimp. During Whales '93, the actual source of this sound was determined when an individual blue whale was successfully tracked for 43 days over a distance of 2,500 kilometers. Given the nickname of "Ol Blue," the blue whale vocalized at a rate of one comma every 74 seconds for most of the 43 days. The constant repetition rate served as a "fingerprint" when the whale was re-acquired after long gaps in time when the whale was not vocalizing. The whale was distant enough from the arrays so that only the comma, or chirp, was observed on the displays.

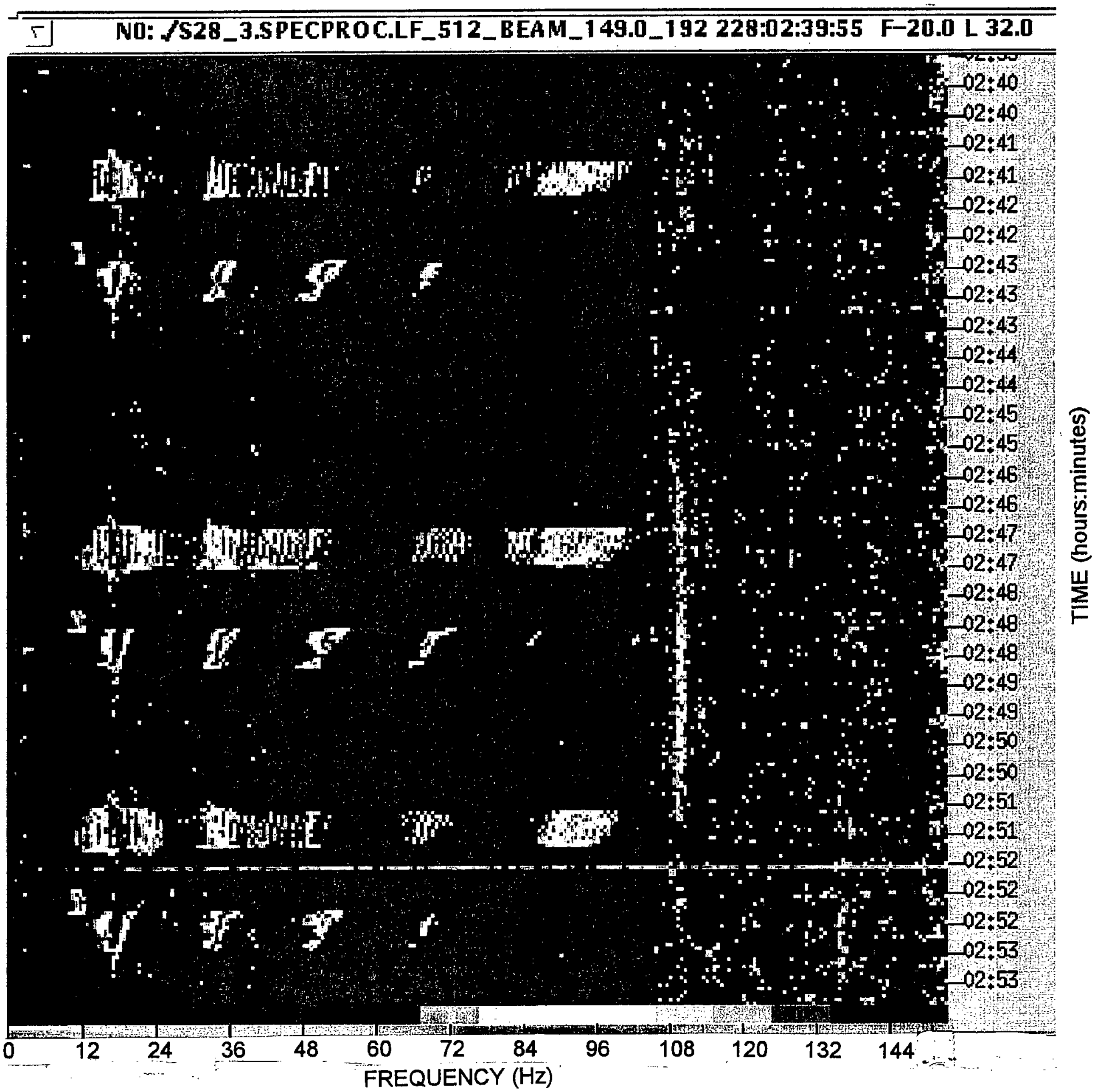

Figure 5. Blue whale vocalizations during Magellan II Segment I.

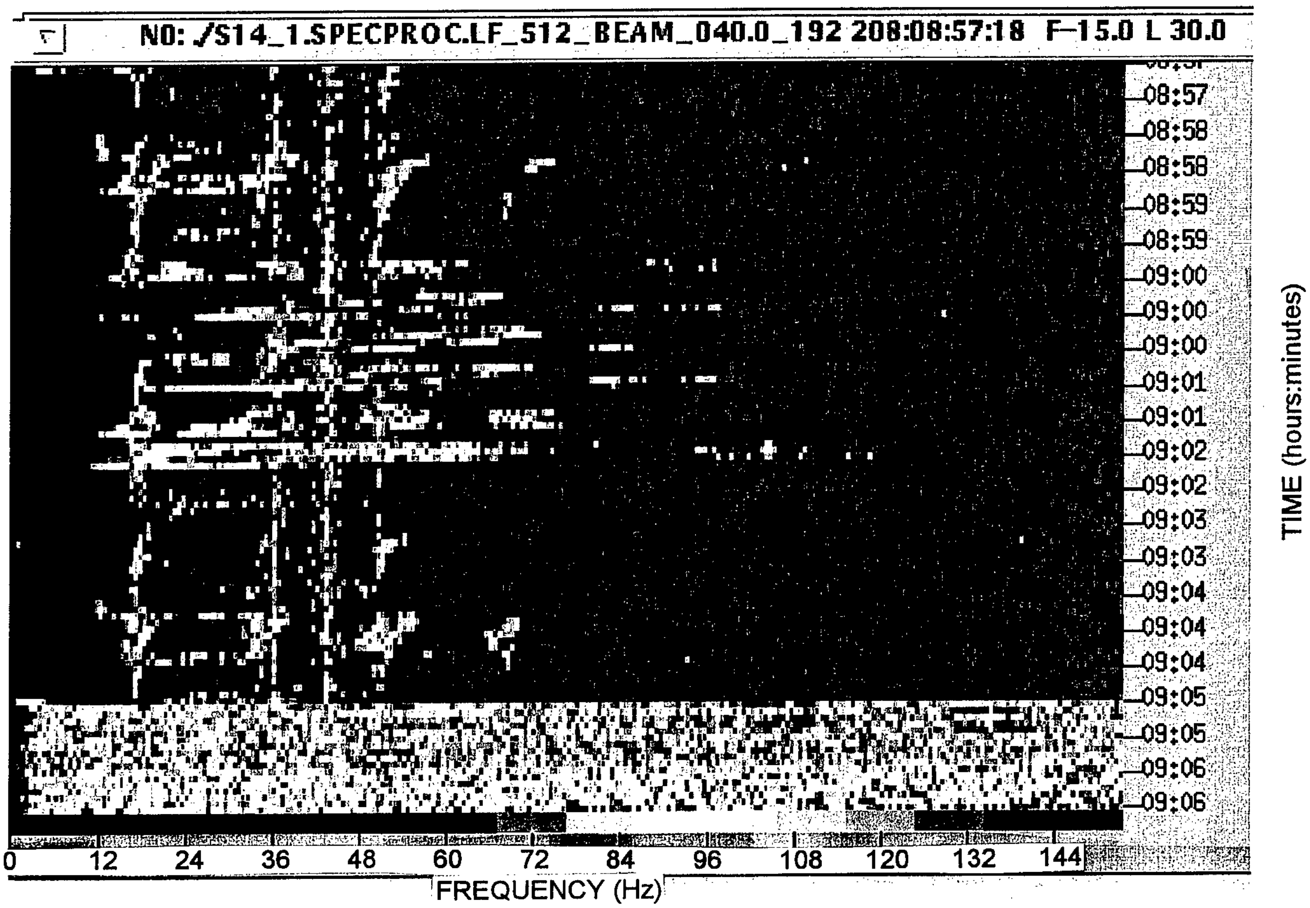

Figure 6. Blue whale vocalizations from 17 to 68 Hz.

1.3.2 FINBACK WHALES

The finback whale (*Balaenoptera physalus*), like the blue whale, is distributed in temperate and cold waters worldwide, as shown in figure 7. Almost as large as a blue whale, the finback whale is considered a highly efficient swimmer and is the second largest of the mysticetes. The average length is approximately 65 feet and females may weigh up to 70 tons. The finback whale is slimmer and more sinewy than the blue whale. Finback whales reach physical maturity at 15 years and their life expectancy is 40 to 45 years or more. When feeding, finbacks swim at 1 to 3.5 kts and can attain speeds up to 22 to 29 kts. Finback whales are gray and have a snow-white throat and belly. As illustrated in figure 8, the flippers are short and the dorsal fin, although longer than that of the blue whale, does not stand more than 27 inches high. A grayish-white chevron runs across the back behind the head and between the flippers.

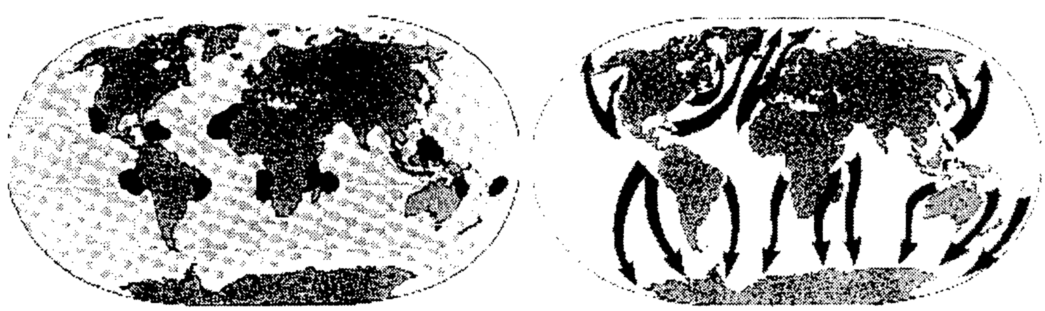

Figure 7. Finback whale breeding areas and migration patterns.

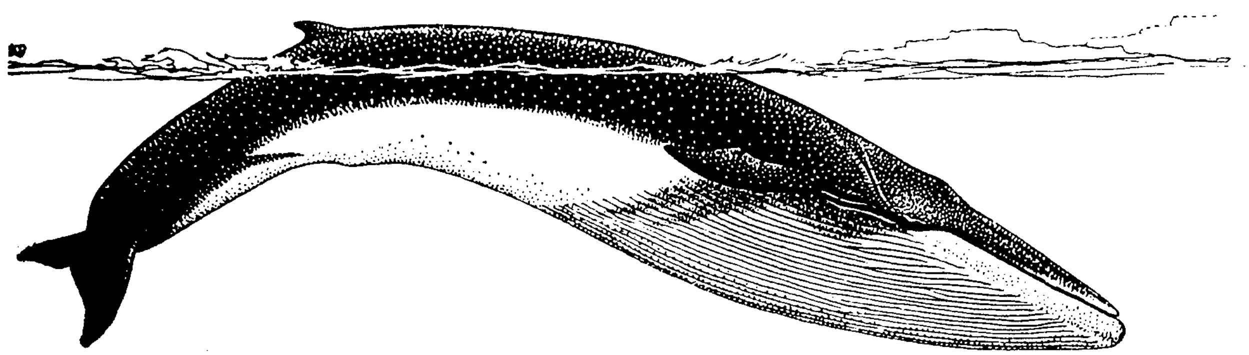

Figure 8. Finback whale (reprinted by permission, Ridgway 1972).

As documented in Whales '93 and other reports (Watkins et al., 1987 and Thompson, 1992), finback whales produce low-frequency sounds characterized by downswept FM pulses of approximately 1-second duration with an interpulse spacing of 7 to 30 seconds. Spectral content is in the 18- to 25-Hz region with a source level of up to 200 dB//μPa @ 1m. A finback vocalization session normally consists of a relatively constant repetition rate with the pattern broken up by discrete rests. Several vocalizing finback whales can be recorded on a single beam, resulting in saturation of the 20-Hz frequency band. In the Navy surveillance community, this biologic sound is referred to as the "Jeze monster." A common finback vocalization is the production of doublet pulses spaced 1 to 2 seconds apart. Finback signals sometimes contain the odd harmonics of the fundamental pulse frequency. The harmonics are smaller in amplitude than the fundamental frequency component and are only recorded when the animal is close to the receiving array. The beam gram of a typical finback vocalization recorded during Magellan II is shown in figure 9.

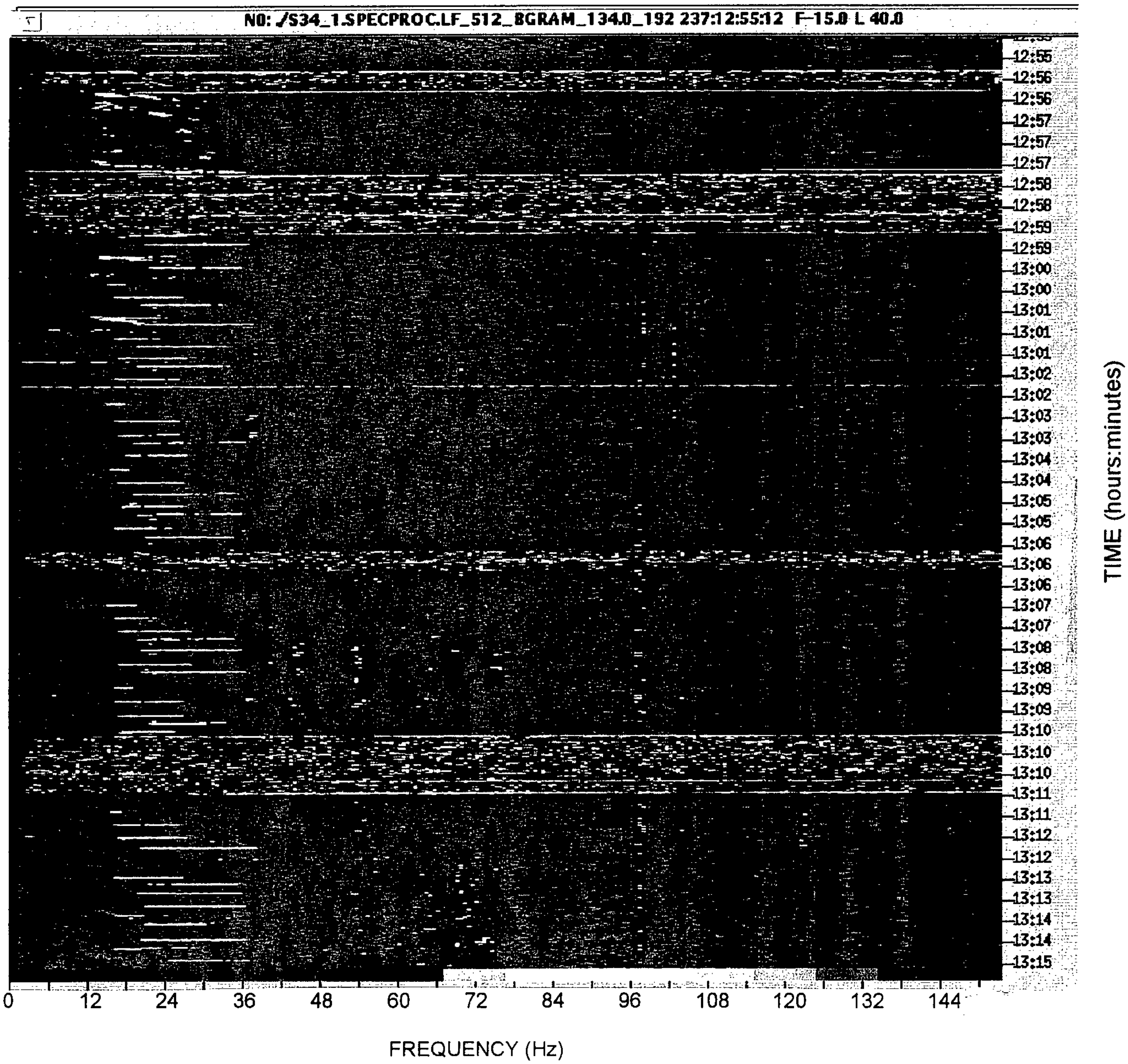

Figure 9. Finback whale vocalizations during Magellan II Segment 2.

2. WHALE DETECTIONS

Cornell University personnel and hardware were aboard R/V *Cory Chouest* (R/V-1) to perform whale-monitoring operations during Magellan II. Cornell's "Popeye" whale monitoring system was the primary component of the monitoring efforts which were designed to detect and track large whales (blue, finback, humpback, minke, gray) which vocalize and have sensitive hearing at frequencies below approximately 500 Hz. The system operates by using near-field acoustic processing to localize the whales as they emit low-frequency vocalizations.

The "Popeye" system was connected to four hydrophones from the receive acoustic line array which was towed behind R/V-1 at a depth of approximately 500 feet. Correlation processing of the received whale signals allows time-of-arrival differences to be estimated which translate to range and bearing (appendix A). A feature that occurs when using this approach from a towed line array is that if the array is towed straight, a left/right ambiguity factor is created. In essence, one would be unable to determine if the acoustic signal is coming from the left or right side of the array due to its symmetry. During Magellan II, the "Popeye" software assumed that the array was always straight, and did not account for the bowed shape that the array generally exhibits. Consequently, the bearings in the R/V Cory Chouest Whale Log were always given between 180 degrees and 360 degrees relative measured clockwise from array forward endfire. Because a single line array was used, localization at or near array endfire was not feasible. However, whales detected on aft endfire are known to be at least 1 nmi distant since the receive array extends more than 1 nmi behind the ship.

The primary purpose of the Whale Monitoring Team and the "Popeye" system aboard R/V-1 was to determine if vocalizing whales were coming within one nautical mile of the sound source which was deployed from the centerwell of R/V-1. In accordance with the mammal mitigation measures, if a whale was detected at or within 1 nmi of the ship, then the LFA active transmissions were suspended. The whale was then tracked until it was determined to be at a range greater than 1 nmi, at which time the active transmissions resumed.

It is important to point out that the team's purpose was not to track whales or understand behavioral patterns but to determine when and if a whale came too close to the array requiring active emissions to stop. The whale monitoring team aboard R/V-1 for the Magellan II Segment 1 at-sea test included Russ Charif (Cornell), Bill Ellison (MAI), Bill Marsh (NRaD), and Cal Matheny (HAC).

Figure 10 shows the overall area in which whale detections occurred during Segment 1 of the Magellan II test. Blue whales were detected more frequently than the finback whales although both were detected every day of the test at ranges from 200 meters to approximately 16 km. In some cases, blue whales were detected for extended time periods of up to 4 hours at ranges greater than 2 km. The blue whales remained in the vicinity of the source ship during periods of relatively continuous active transmissions.

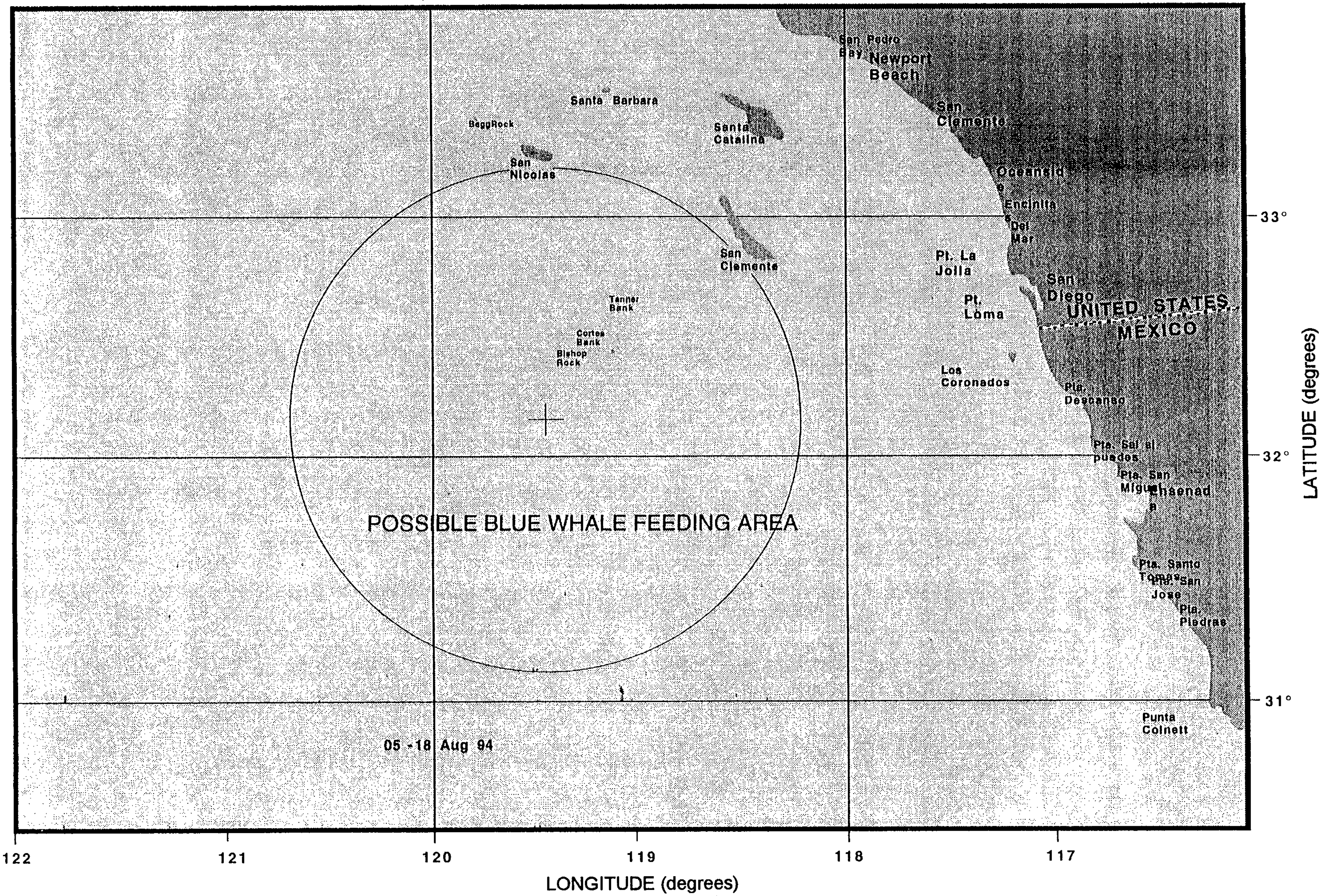

Figure 10. Whale detection area.

It was discovered during the test that the blue whales tended to congregate in a shallow water area in the vicinity of 32-07.5N, 119-29.5W. R/V-1 transited through this area on 14 August. On the following day, R/V-1 approached the site again and found blue whales still congregated in the same area. The pod of whales did not swim away from R/V-1 as it approached while transmitting. During this portion of the test, a blue whale came within close range of the array where it was possible to obtain a good fix of its location and to measure its received sound level on a hydrophone.

Blue whales were the dominant species detected during Magellan II Segment 1. Some finback whales were also detected during this portion of the test and are distinguished from blue whales by the different acoustic characteristics of their vocalizations.

Overall, blue whales (and finbacks less frequently) were detected during every day of the at-sea test from ranges of 200 meters to a maximum of approximately 16 km.

In general, there is nothing in the R/V-1 Whale Log that indicates the whales tried to distance themselves from the active transmissions. In fact, the blue whales seemed 'curious' about the active signals since they displayed a behavior pattern of closing range on R/V-1 to several hundred meters (note active transmissions were turned off when they were within 1 nmi of R/V-1) where they remained for several minutes until they opened range again on a reciprocal course back to the general location from which they came. It is speculated they may have rejoined a group of whales feeding locally, or migrating to their northern habitats.

In the R/V-1 Whale Log it was also stated that blue whale vocalizations were observed to occur during active transmissions. This is significant perhaps because the whales appear to ignore the R/V-1 active transmissions. However, given the amount of blue and finback data available from Magellan II, it would be very useful to conduct a statistical analysis of the relationships between whale vocalizations and active transmissions as observed on the receive array. Such issues as how often the whales stopped vocalizing after a ping, or how often they vocalized during pings could be answered via tape playback.

When a blue whale came within close range of the array it was possible to obtain a good fix of its location and a measure of the received sound level on a hydrophone. This enabled the sound level emitted by the whale, or the whale's source level, to be estimated. The source level estimates were approximately at a peak level of 190 dB re 1μPa @ 1m for the blue whale 17-Hz signal. It is impressive that blue whales can achieve these levels since these are very high source levels at 17 Hz relative to our current technology. It is important to realize that at 1 nmi from the source array, the levels of sound generated by LFA are far below the peak level 190 dB re 1μPa @ 1m sound levels generated by blue whales themselves.

3. WHALE DETECTIONS, POST TEST RESULTS

This section provides more detailed analysis of the Magellan II Segments 1 and 2 LFA receive acoustic array data tapes.

3.1 PROCEDURES

Data were recorded continuously aboard R/V *Cory Chouest* on Very Large Data Store (VLDS) tapes. Each tape holds approximately 80 minutes of hydrophone digitized time series data from the receive towed hydrophone array. The low-frequency (LF) aperture of the towed array is quite large, with the overall array spanning a length of nearly 1 nmi. Based upon inputs from the Marine Mammal Mitigation team and an examination of their log, 12 whale detection events were selected for follow-on analysis. Each event was intended to be covered continuously for 4 hours. This translates to three VLDS tapes per event for a total of 36 VLDS tapes and nearly 400 Gbytes of data. Copies of the archived VLDS data tapes were obtained from Hughes Aircraft Inc. These VLDS data tapes were transferred to 8 mm (Exabyte) data tapes for convenience in processing and analysis on Sun UNIX computer systems. Appendix C shows a list of the Exabyte tapes and the selected date-time groups. At the same time that the data was transferred from VLDS to Exabyte it was decimated to cover a frequency range from 0 to 153.6 Hz. Fast Fourier Transforms (FFTs) were also done on each hydrophone time series such that the frequency bin spacing was 0.6 Hz corresponding to an FFT epoch of 1.67 seconds. This was adequate to resolve the frequency and time structure of the 20 second blue whale and 1-second finback vocalizations.

In conducting the analysis, the first task was to determine bearings to blue and finback whales from identifiable vocalizations. This was accomplished by using the entire acoustic array of hydrophones to form beams covering look directions, or beam-bearings, from forward end-fire to aft end-fire in 1-degree increments over the acoustic frequency band from 14.4 to 19.8 Hz. This band was chosen because the blue and finback vocalizations peak (are strongest) in this frequency range. The power in this band (in dB) is plotted for each beam for each FFT epoch. This type of plot is called a Bearing (Beam) Time Recording or simply a BTR. Figure 11 is an example BTR of about 15 minutes duration from Magellan II Segment 1. The horizontal axis, or x-axis, is the beam relative bearing in degrees, and the vertical axis, or y-axis, is time (one scan or FFT epoch every 1.67 seconds). A beam relative bearing of 0 degrees corresponds to aft endfire. The relative beam-bearings go around clockwise from aft endfire. The beam at relative bearing 090 degrees is port broadside and the beam at 180 degrees is forward endfire. Since the array data are processed assuming a single straight line array, it is impossible to distinguish left (port) from right (starboard). For example, the data from the beam at relative bearing 090 degrees are identical to that from 270 degrees.

Figure 11 illustrates other commonly occurring features of the data. The dark red bands at 16:44, 16:45, and between 16:51 and 16:52 are the result of active emissions (pings) that

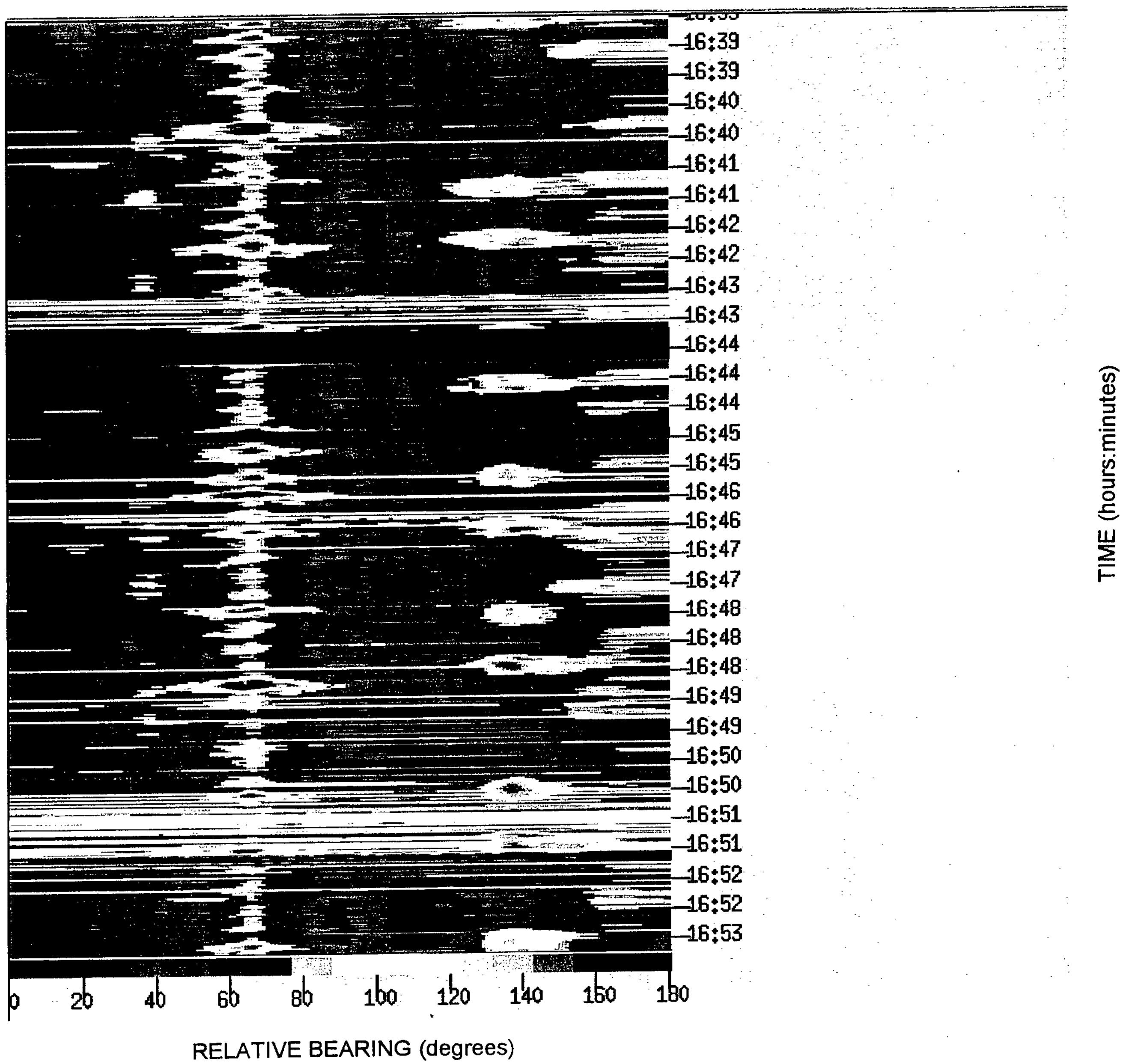

Figure 11. Example BTR plot (181639Z to 181653Z Aug 94), 14.4- to 19.8-Hz band. Black 15 dB, red 54 dB, 16 colors. Array heading 290 degrees true.

overload (exceed the dynamic range) the receive array hydrophones, resulting in a more or less constant clipped level across all frequency bins. There are also yellow horizontal strips that are often observed across the BTR. These are due to data outages that occurred either during the tape recording or tape reproduction (dubbing) process. In several instances the VLDS or Exabyte tapes were partially or totally unreadable. Figure 11 also clearly indicates five relative beam-bearing directions to sound sources in the 14.4- to 19.8-Hz band which may be due to blue or finback whales. These are beam-bearings of 19, 36, 67, 137, and 167 degrees. Beams 19 and 36 show what may be blue whale vocalizations but they appear to be weak and distant. Beam 67 shows very strong signals but they do not exhibit the blue or finback vocalization patterns discussed earlier in section 2. Beam 137 very clearly illustrates a blue whale vocalization pattern of high signal strength, which indicates the blue whale was relatively close to the array. Beam 167 may also indicate a blue whale signal that was close to the ship near forward endfire.

To understand the signals in these beams we examine the time histories of the spectra for each beam of interest. These type plots are called beam-grams. In these plots the x-axis is frequency, and the y-axis is time. The gram of beam 19 is shown in figure 12. If we examine the 14.4 to 19.8 Hz region of this beam gram we can make out a faint trace of a blue whale 'trill' at 16:40 and a 'chirp' near 16:41 and also at 16:44 and 16:47. This whale vocalization is too distant (the signal is too weak) to be of interest at this time. Figure 13 also shows possible blue whale calls on beam 36. They are stronger than those on beam 019 but are washed out by other noise that is actually side-lobe energy (leakage) from beam 67. Figure 14 shows the gram of beam 67. This shows very powerful frequency up-sweeps from 12 to 48 Hz and centered at 30 Hz. The true bearing of this source was approximately 177 degrees. At first, during Magellan II Segment 1 it was thought that these powerful up-sweeps were marine mammal in origin but since the up-sweeps were continuous, without a pause, it was finally decided they were seismic in origin. This up-sweep became known as "Seismic Blue" or "Volcanic Blue" during the Magellan II Test. It was observed throughout the test (July-September 1994) and it remained at a bearing of approximately 177 degrees, indicating an origin far to the south in the volcanically active East Pacific Rise area off the western shores of South America. Figure 15 is a gram of beam 137. It clearly shows blue whale vocalizations, as described in McDonald et al. (1995) amid the pings. This type of blue whale vocalization pattern was analyzed to determine if the pattern was disrupted or altered by the pings. The blue whale ranges from the array were also checked to determine if they changed significantly after the pings. It was primarily by these two methods that blue whale reactions to the high-level pings were inferred.

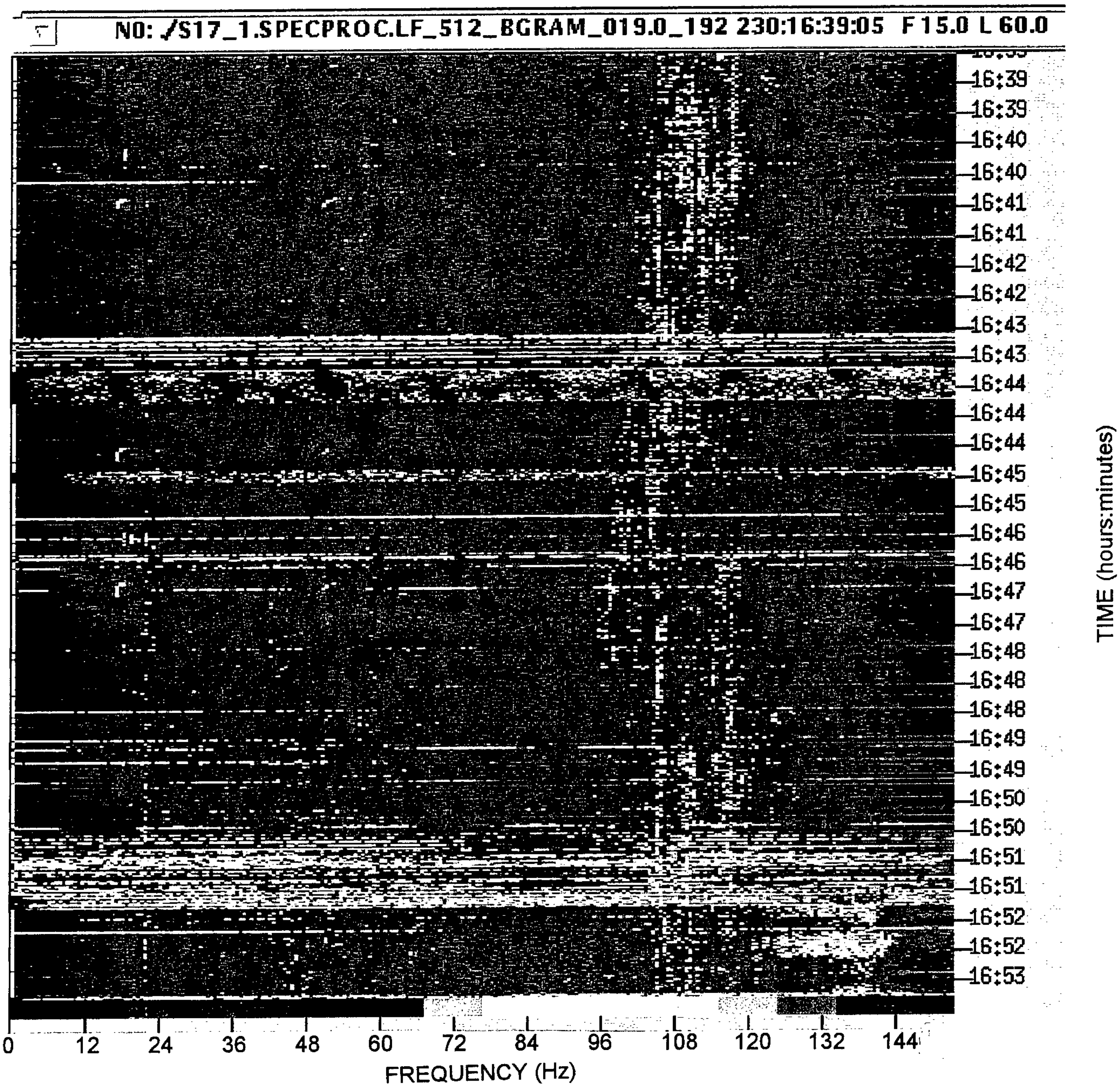

Figure 12. Gram of beam 019, tape S17_1, 181639z August 1994.

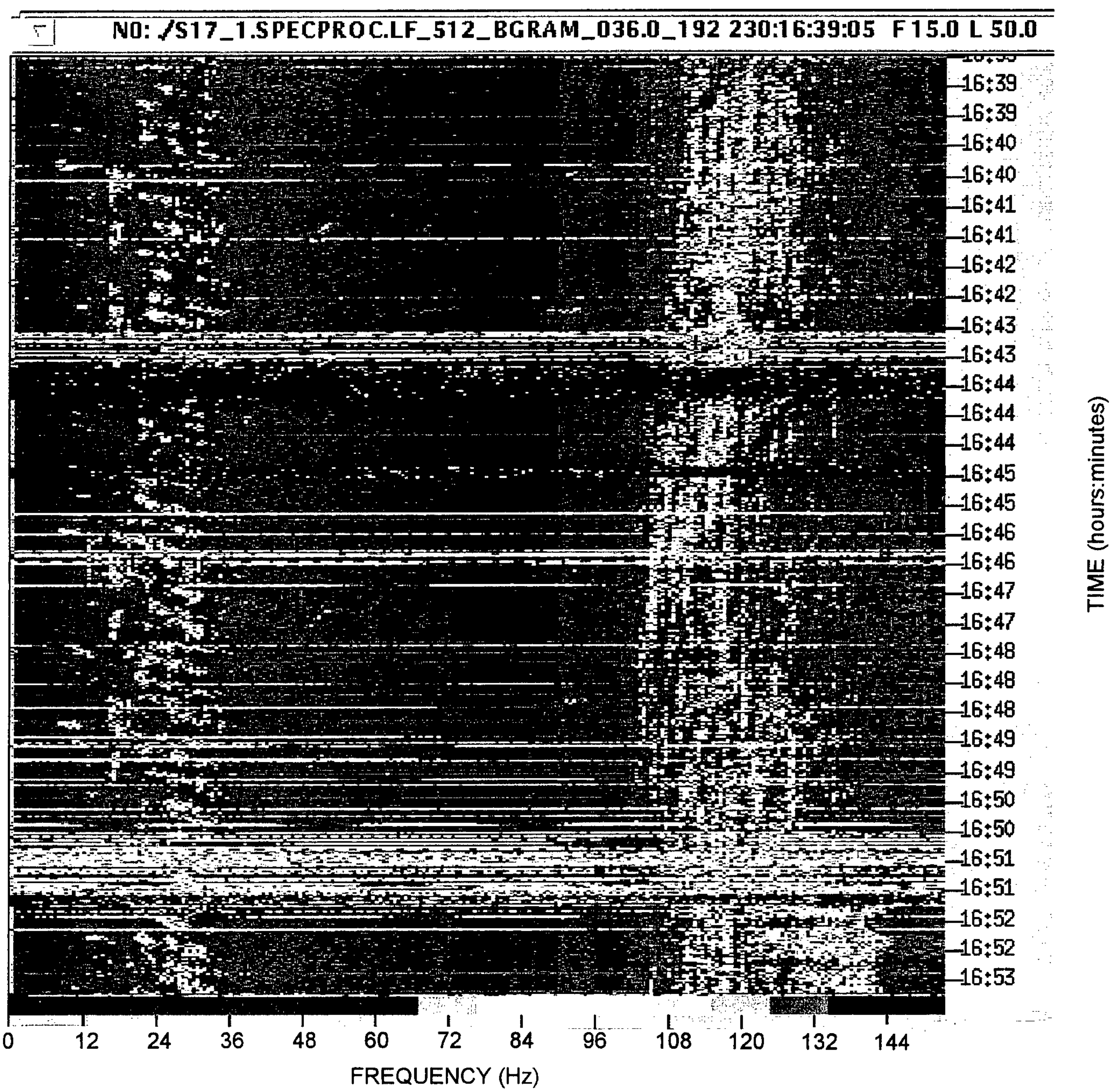

Figure 13. Gram of beam 036, tape S17_1, 181639z August 1994.

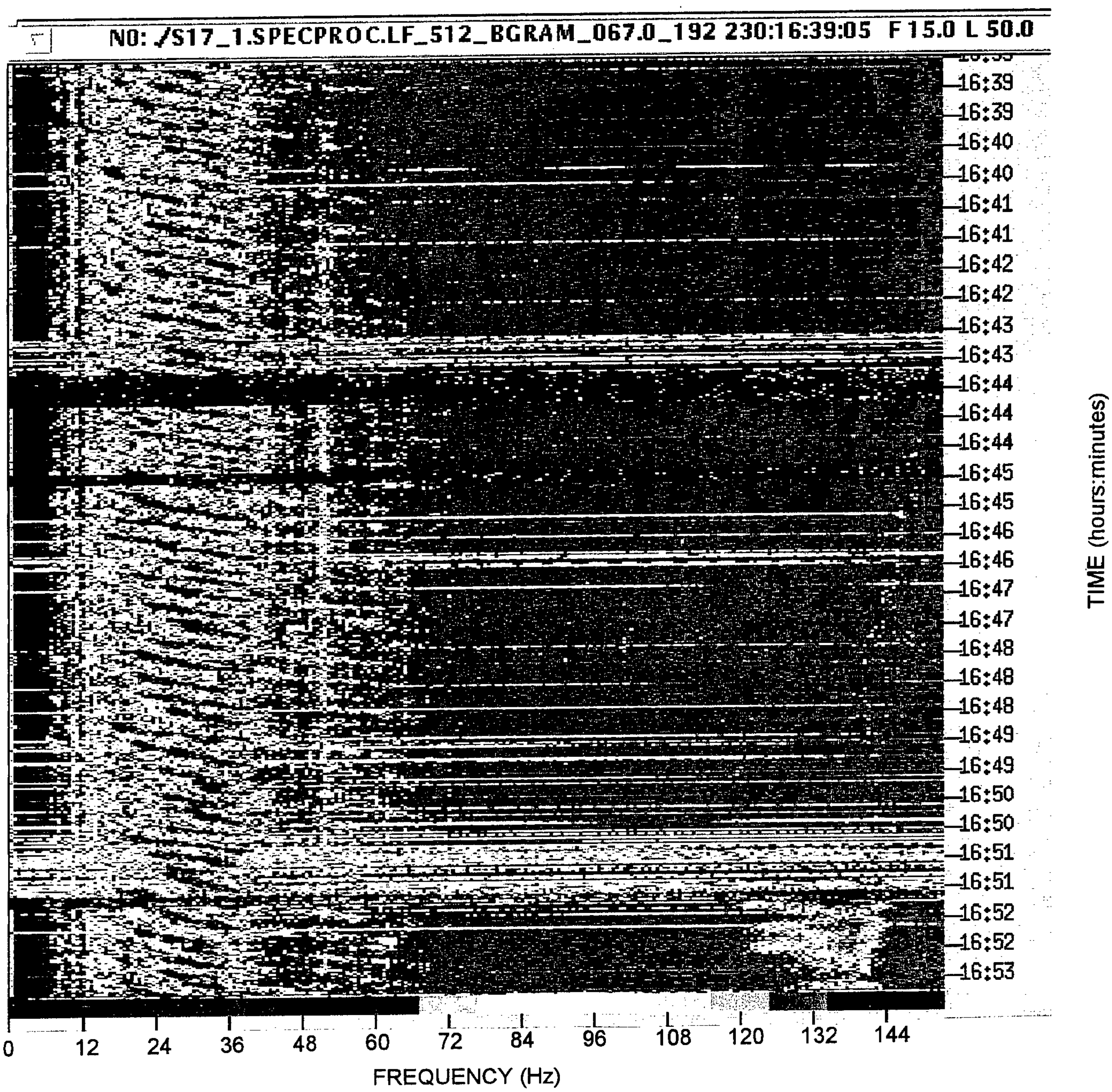

Figure 14. Gram of beam 067, showing "Seismic Blue", tape S17_1, 181639z August 1994.

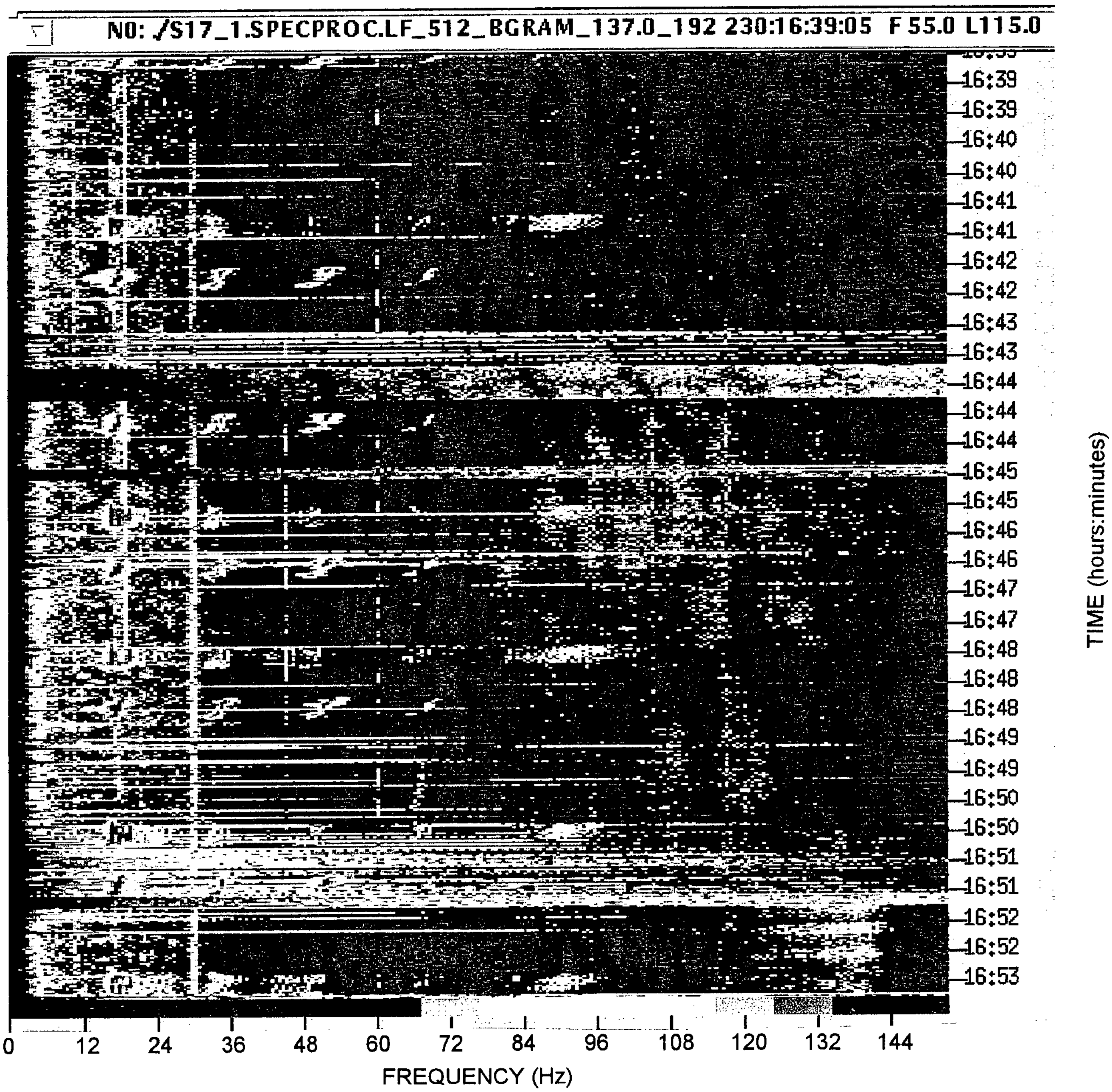

Figure 15. Gram of beam 137, with blue whale vocalizations. Tape S17_1, 181639z August 1994.

The range estimation, in this report, is done using subarray cross-fixing. The geometry with the equations needed are provided in appendix B of this report. BTRs are formed from 48 phone subarrays at each end of the towed array. The centers of the 48 element subarrays are separated approximately by only 0.71 nmi so that the maximum detection ranges will be limited to a few nautical miles although the sensitivity of the full array allows detections of whales to hundreds, and even thousands, of miles in the open ocean. Since the array shape changes as it is towed, the orientation of the forward and aft subarrays may not be the same (which would cause a range estimation error). Thus heading sensors in each subarray are used to align the heading of each subarray to the average heading of the entire array. Figure 16 shows the forward subarray BTR, and figure 17 the aft subarray BTR for the same data. The bearings in each plot have been rotated for each epoch so that both subarrays have the same base heading. The rotation for this data set is actually very slight as the array was being towed very steady and straight. The amount of rotation is apparent along the left edge of figure 16. It increases from 0 degrees to about 2 degrees near the bottom. The aft subarray showed a steady 1 degree rotation that is apparent on the right side of figure 17. The high-intensity noise at the relative bearing of 67 degrees in figures 16 and 17 is the distant seismic noise that was called "Seismic Blue", or "Volcanic Blue", during Magellan II Segment 1. Since it is known to be at great distance to the south, it is expected that both subarrays will show the same bearing, and, happily, that is exactly the case as shown in the figures. An indicator that the array is being towed steady and straight is the fact that the seismic noise is steady at beam/bearing 67 throughout the time period. That is, if the array moved, the apparent relative bearing to the seismic noise would shift. Blue whale vocalizations are apparent near beam/bearing 140 in these figures. It is clear that there is some parallax as the blue whale bearing shifts from forward subarray to aft subarray near beam 140 at 16:53 for example. Figure 18 shows the bearings of both the forward and aft subarrays for the FFT time epoch of 16:53:13.2. The bearing of "Seismic Blue" shows no parallax (bearing shift) because it is a very distant source. The fact that both subarrays give the same bearing for "Seismic Blue" is a good indicator that the subarrays are properly aligned. "Seismic Blue" serves well as a bearing calibration source. From the forward and aft subarray blue whale bearings one calculates the blue whale ranges as 3 nmi from the forward subarray and about 3.5 nmi from the aft subarray. In practice, to reduce the error, an average bearing is calculated over the 25-second whale vocalization, and then the range is computed from the average bearing. Since each FFT epoch is 1.67 seconds in duration, there are a maximum of 15 bearing estimates over the 20- to 25-second vocalizations.

This completes the summary of the analysis and procedures adopted for this report. The rest of this section will be devoted to a summary of the specific cases examined.

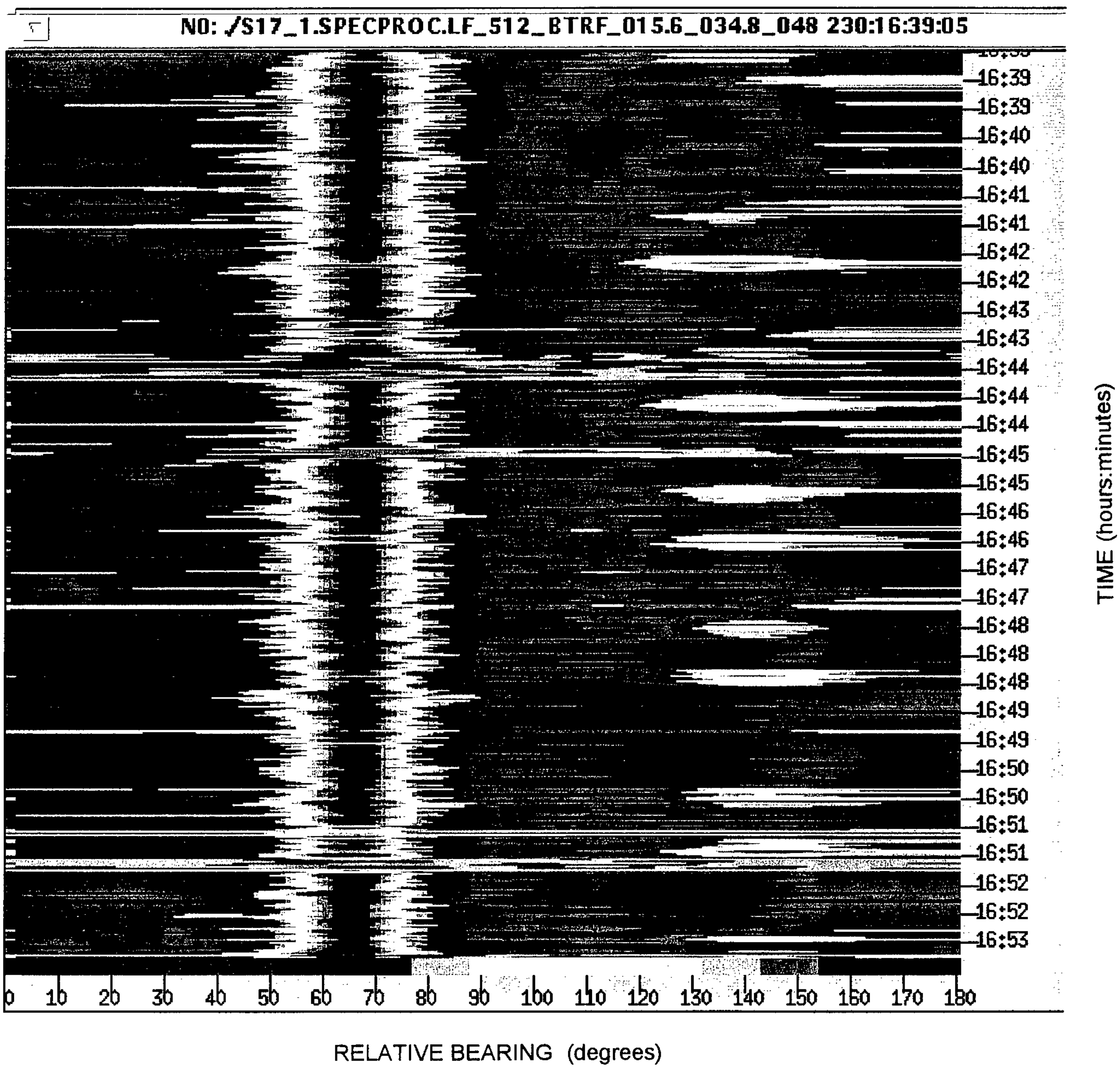

Figure 16. Forward subarray BTR.

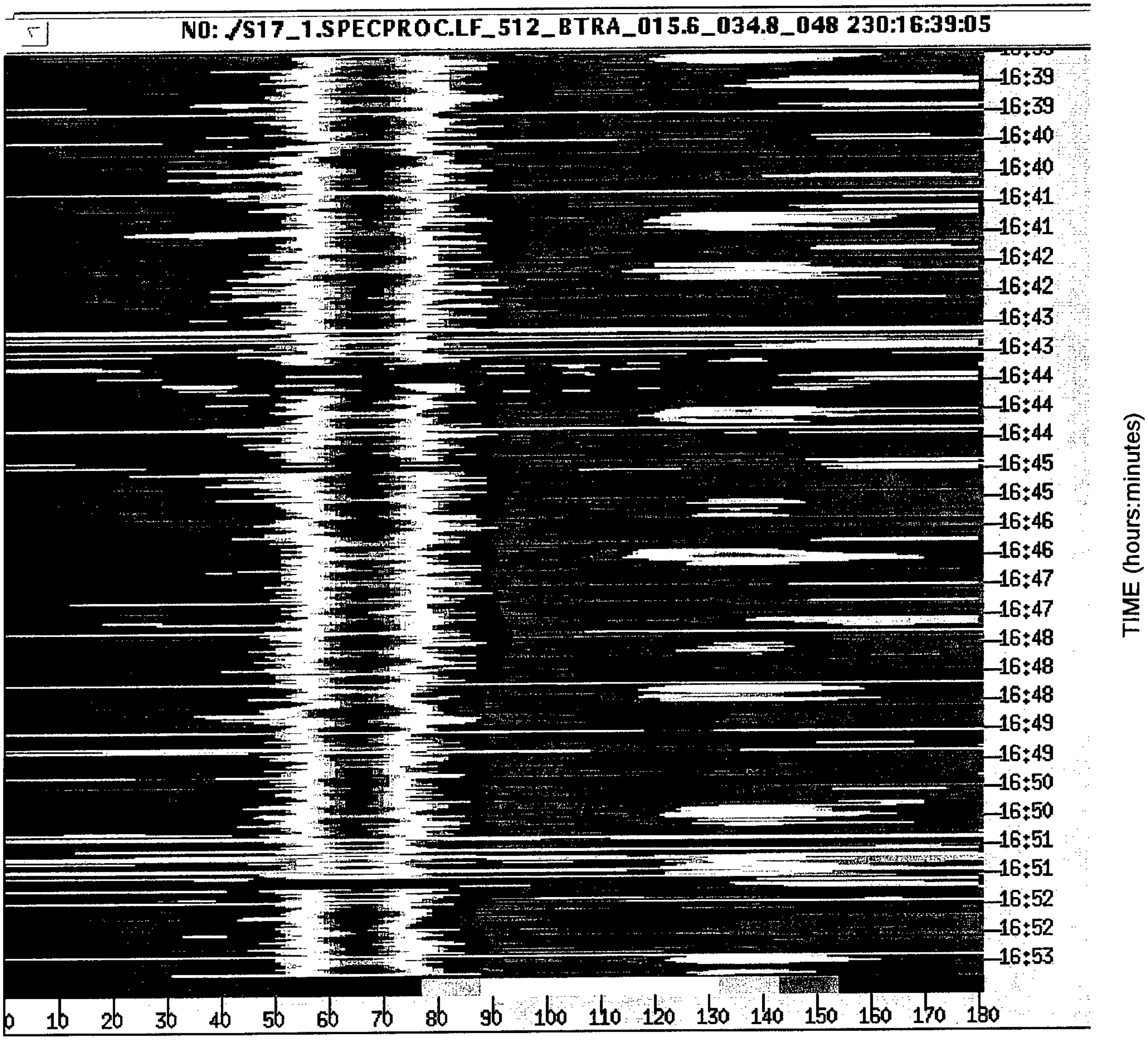

Figure 17. Aft subarray BTR.

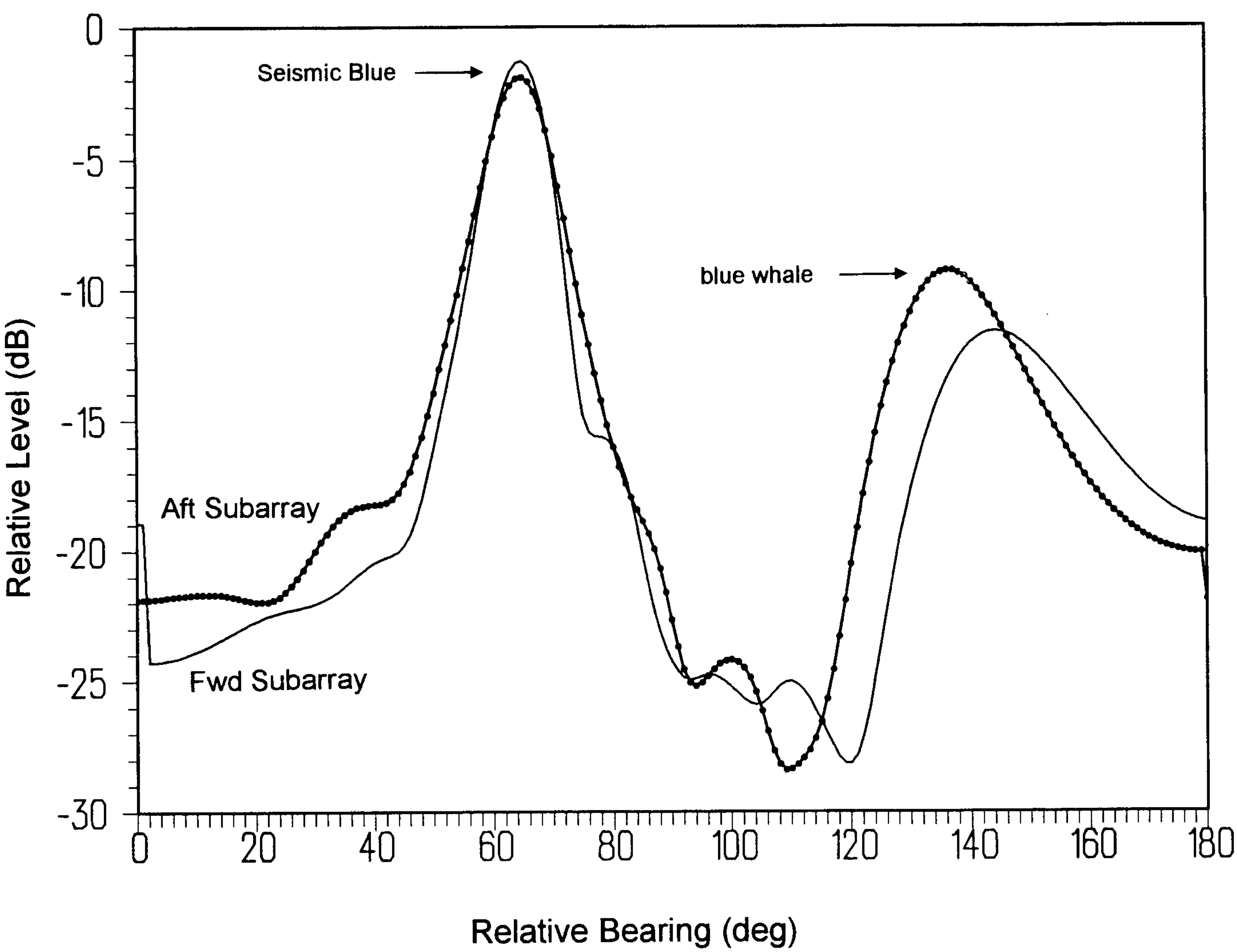

Figure 18. Forward and aft subarray bearings to blue whale at 181653Z August 1994, indicates blue whale range 3 nmi from aft subarray.

3.2 ANALYSIS

3.2.1 VOCALIZATION PATTERN

Two distinct blue whale detections were selected for closer study in the data set analyzed below. The data were recorded during Segment 1 of Magellan II during the interval 16:07:40Z to 18:46:36Z, August 18, 1994. The BTRs for this interval are shown in figures 19 to 26. These BTRs show the energy in the 5.4 Hz band around the 17 Hz fundamental tone of the blue whale calls. Figure 19 shows the first detection at 16:07:40Z of the whale designated blue whale 1 on beam 136. Blue whale 2 was first detected at 16:58:50Z on beam 121 as shown in figure 22. The seismic energy referred to as "Seismic blue" (beams 60 to 70) can be seen in all the figures.

Blue whale 1 vocalizations exhibited the previously documented alternating trill and chirp pattern (McDonald et al., 1995). A summary of blue whale 1 vocalizations and the source transmissions (pings) which occurred during this interval is contained in table 3. The average duration of the trills, chirps, and breaks between them are listed at the bottom of the table. The mean duration of the longer breaks between the trill/chirp pairs is not calculated since these breaks have a pattern consisting of five or six approximately 60 second breaks followed by a longer break of approximately 160 seconds. This pattern of breaks is consistent with that observed by (McDonald et al., 1995). The trill and chirp pattern did not appear to be disrupted by any of the 14 pings that occurred in the interval.

The blue whale 1 beam grams are shown in figures 27 to 33. Several instances of when whale calls overlapped or were in close temporal proximity to pings are evident. For example in Figure 31, the third trill started during the source transmission and the following chirp concluded during the end of the same transmission. The sixth chirp in this sequence occurred almost simultaneously with the second transmission. In neither of these cases, did the frequency characteristics or repetition rate of the vocalizations appear to be altered by the source transmissions.

The distinctive alternating trill and chirp pattern of blue whale 1 is evident in all the figures. In figure 33 for example, the pattern consists of a set of three trill/chirp pairs followed by a 157 second break, and then a second set of three trill/chirp pairs. There is a source transmission in each set which appear to have no effect on the trill/chirp durations or the interval between them.

Blue whale 2 exhibited a vocalization pattern different from the more characteristic alternating trill and chirp pattern previously noted. Its vocalizations consisted primarily of consecutive chirps, punctuated by an occasional trill (58 chirps, 11 trills total in this data set). The blue whale 2 vocalization and ping summary is contained in table 4. The mean duration of the chirps, trills, and the breaks between them is calculated in the table's last row. It is interesting to note that the average durations of the blue whale 2 chirp and trill were approximately 3 and 1.4 seconds shorter, respectively, than that of blue whale 1. The breaks between blue whale 2 trills and chirps were of more variable duration, however the 74 second break is probably an artifact caused by a ping which

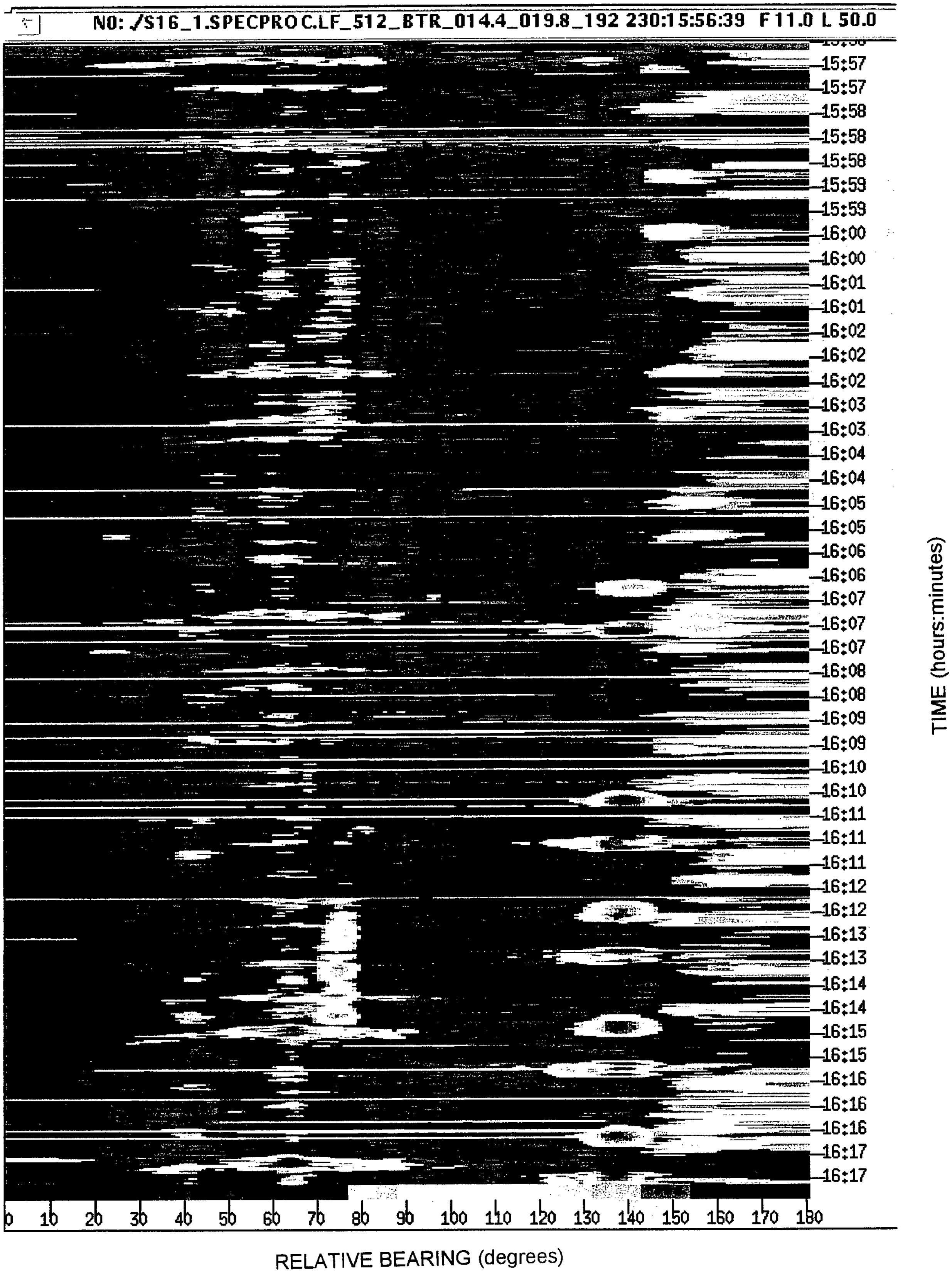

Figure 19. BTR of blue whale 1, 14.4- to 19.8-Hz band, tape S16_1, 181557Z, August 1994.

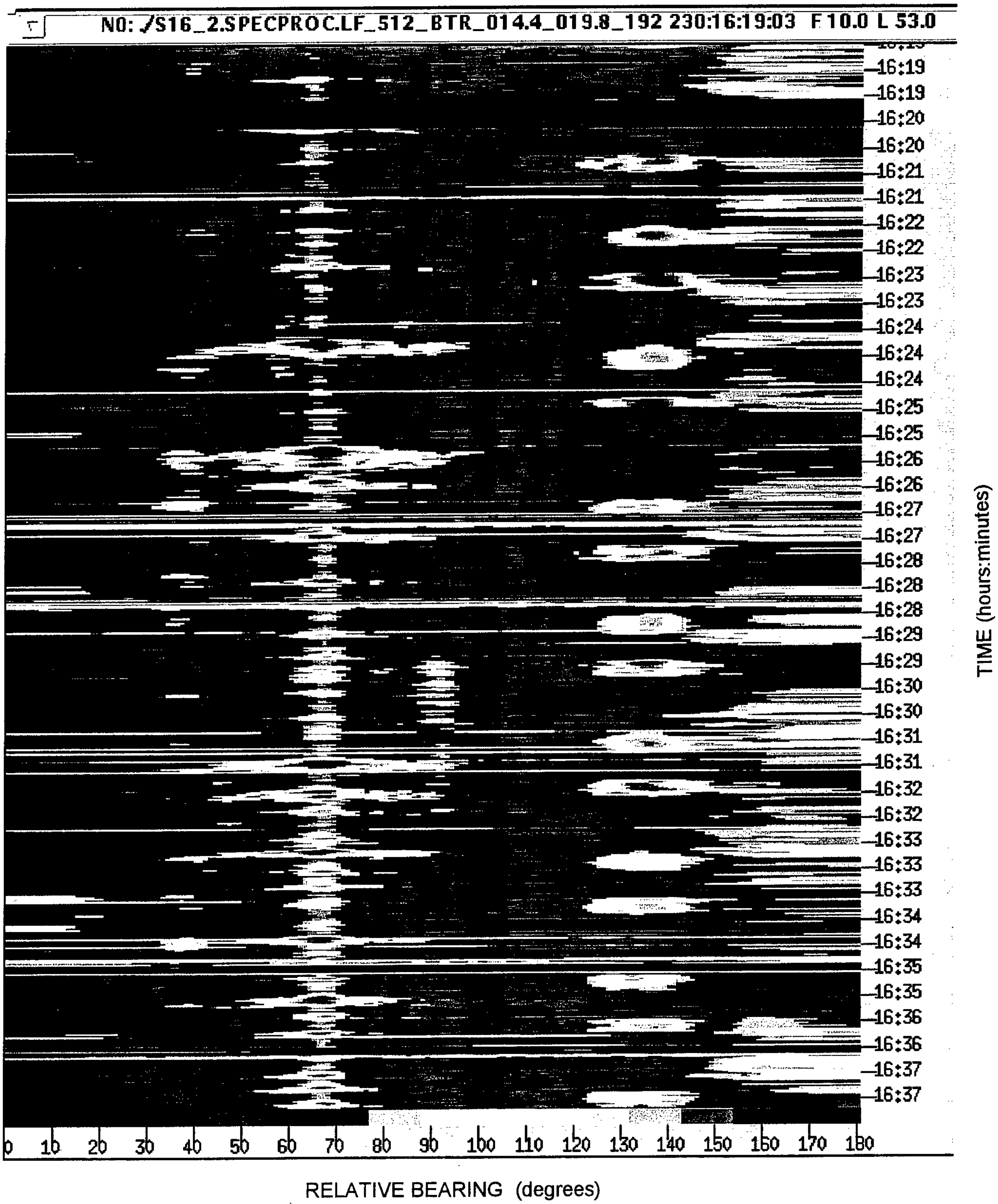

Figure 20. BTR of blue whale 1, 14.4- to 19.8-Hz band, tape S16_2, 181619Z, August 1994.

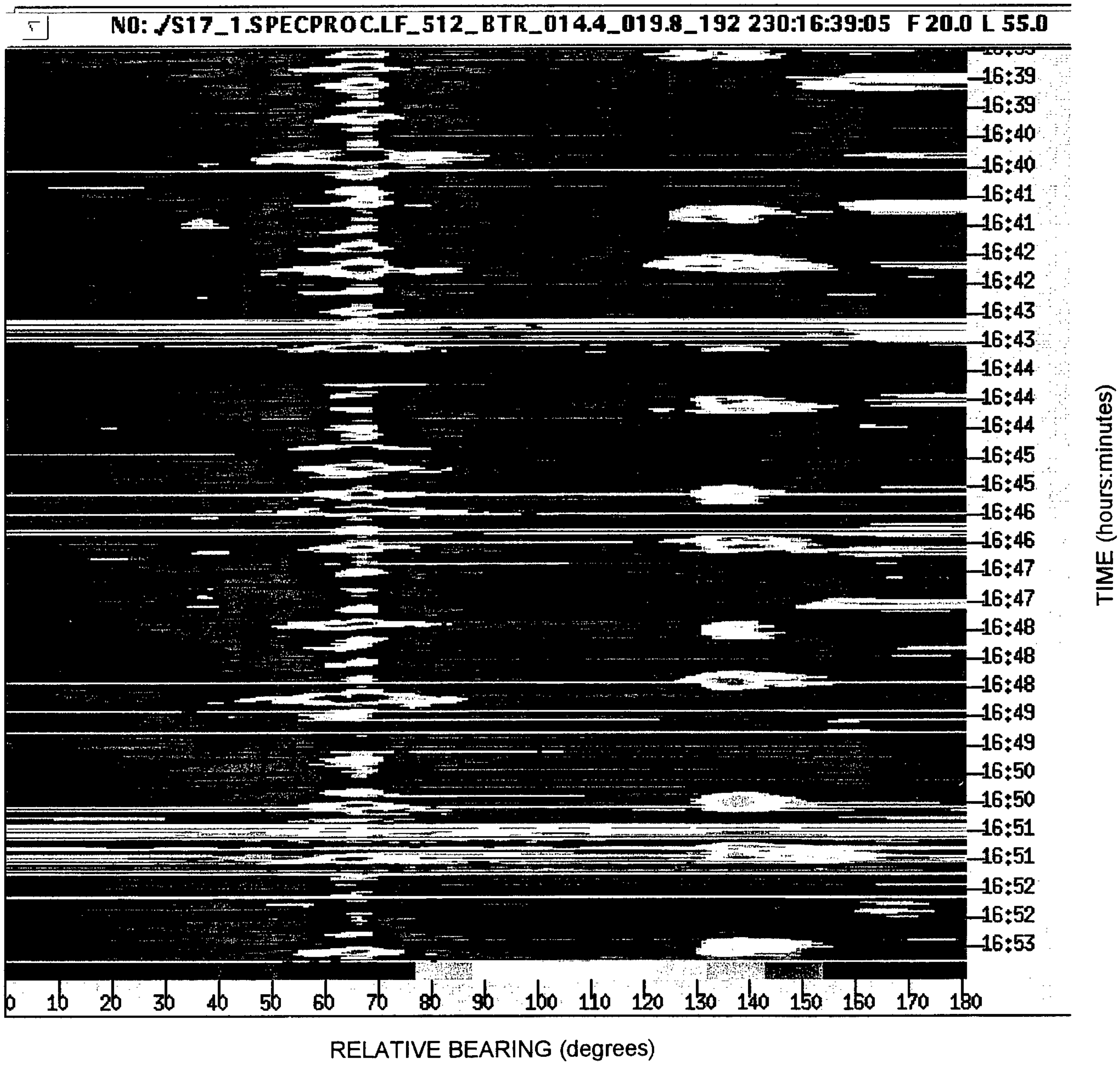

Figure 21. BTR of blue whale 1, 14.4- to 19.8-Hz band, tape S17_1, 181639Z, August 1994.

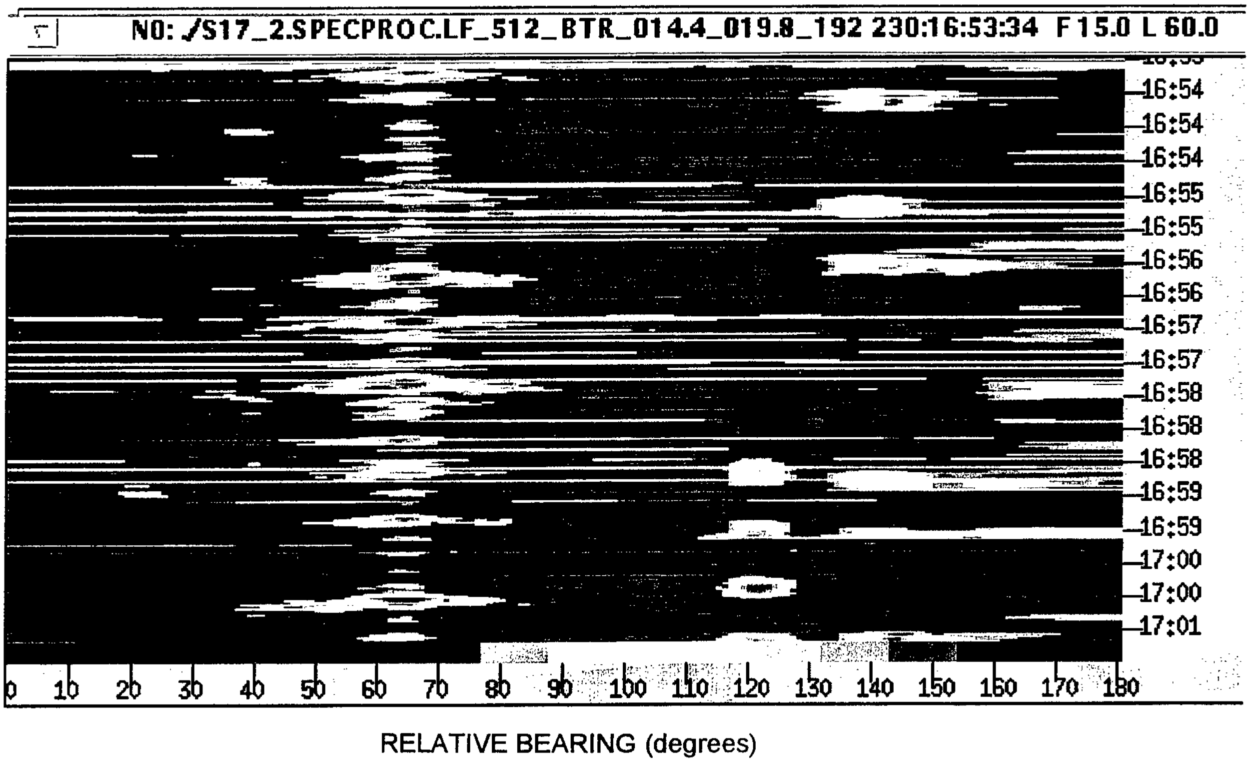

Figure 22. BTR of blue whales 1 and 2, 14.4- to 19.8-Hz band, tape S17_2, 181654Z, August 1994.

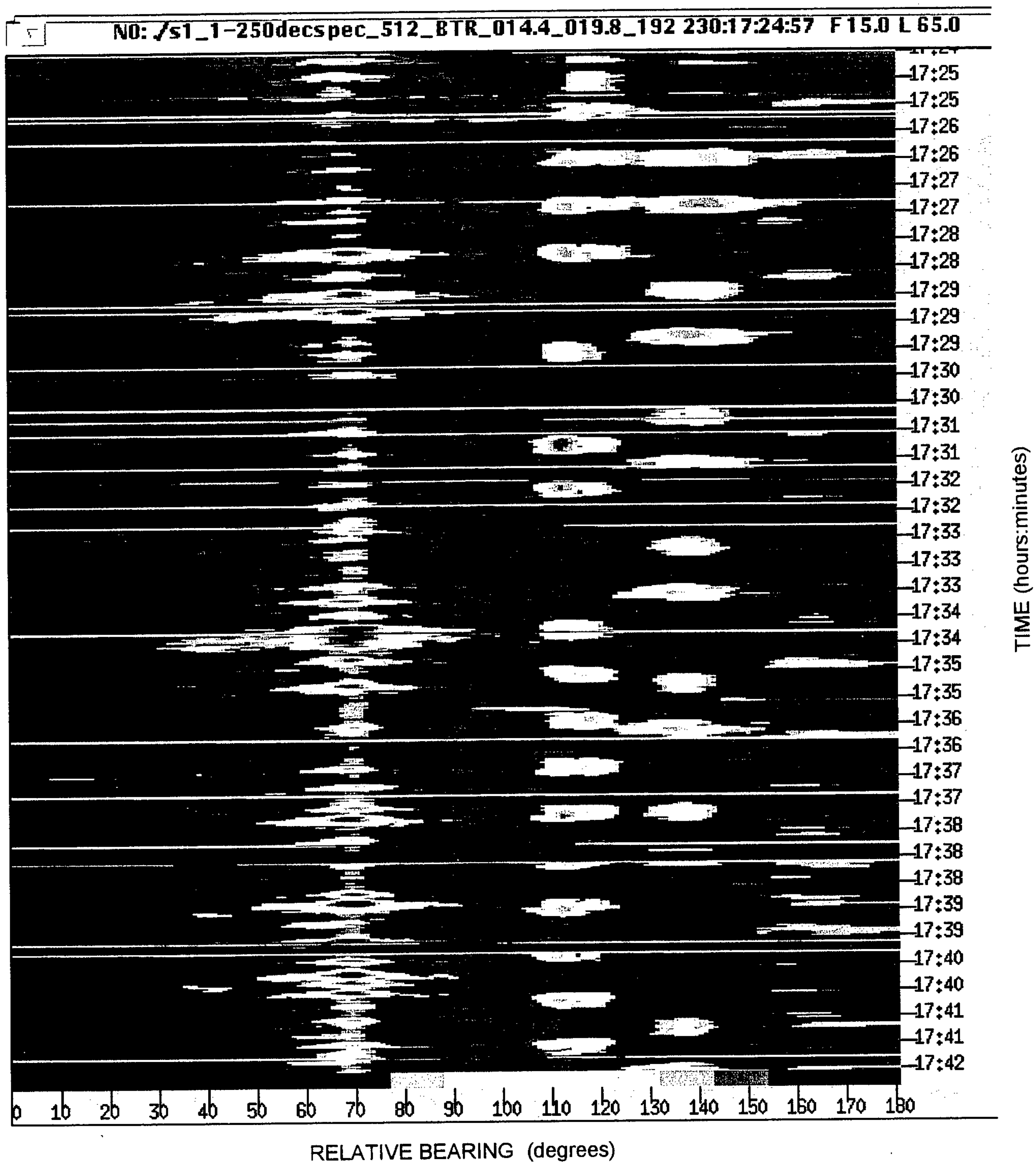

Figure 23. BTR of blue whales 1 and 2, 14.4- to 19.8-Hz band, tape S1_1, 181725Z, August 1994.

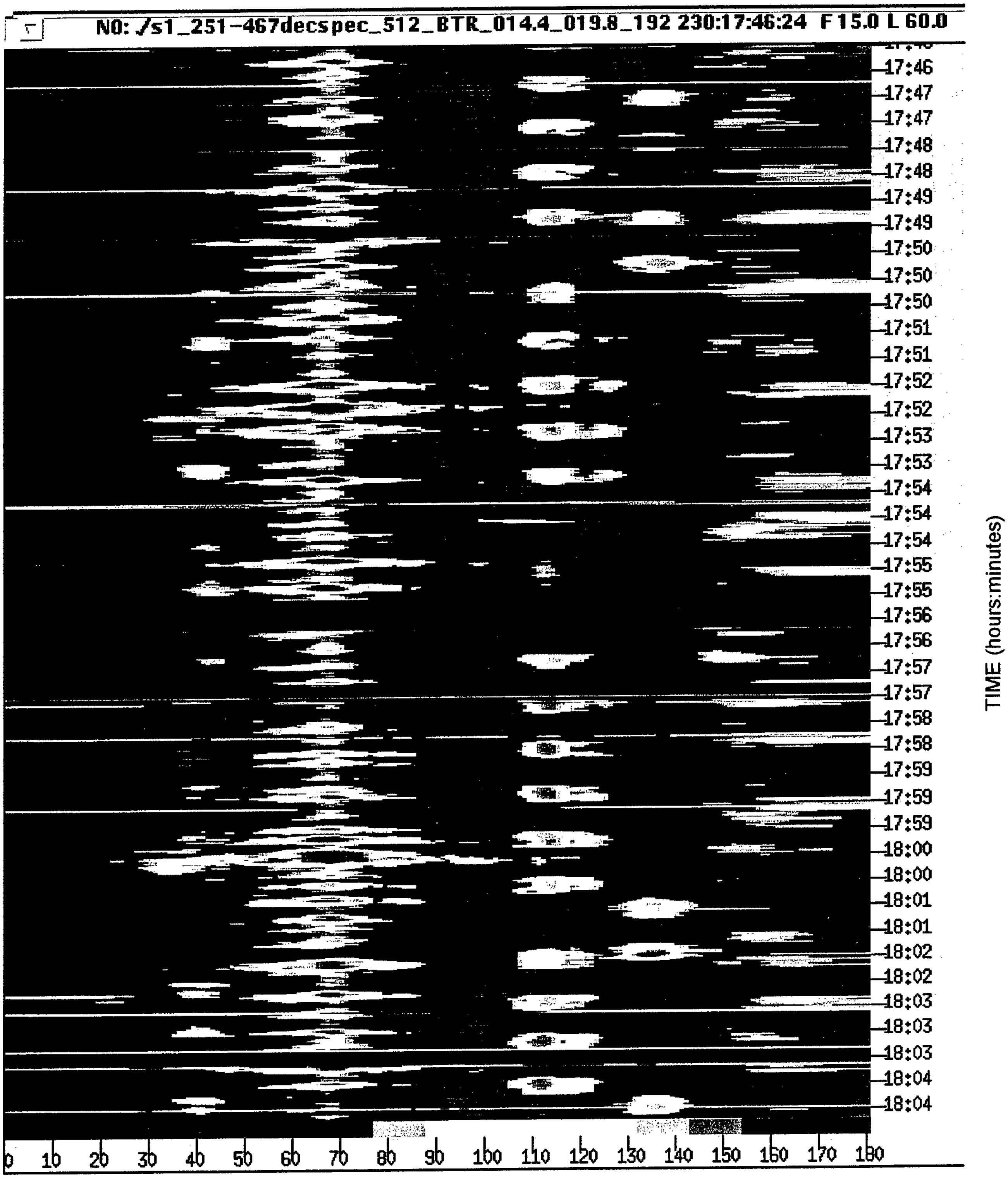

Figure 24. BTR of blue whales 1 and 2, 14.4- to 19.8-Hz band, tape S1_2, 181746Z, August 1994.

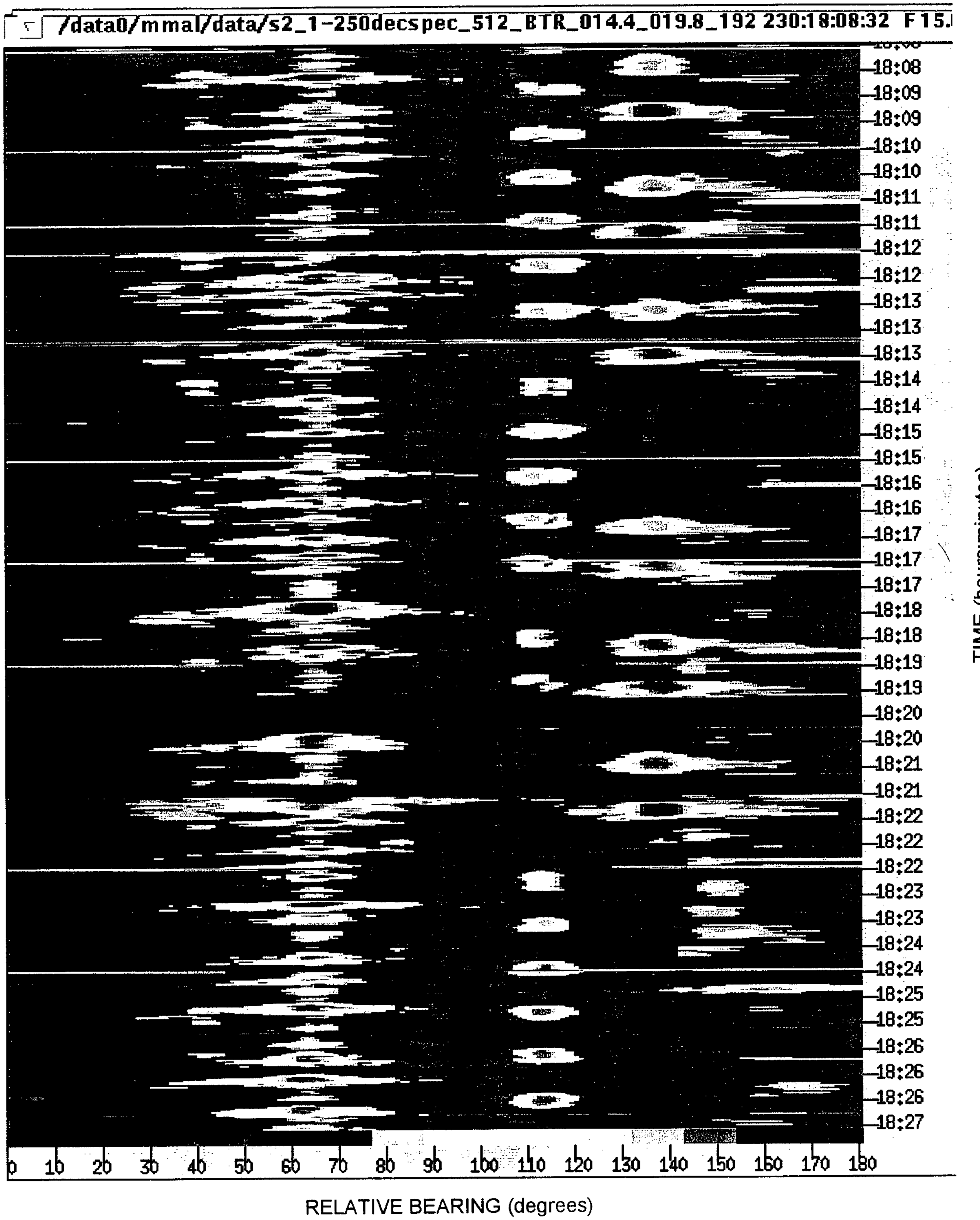

Figure 25. BTR of blue whales 1 and 2, 14.4- to 19.8-Hz band, tape S2_1, 181808Z, August 1994.

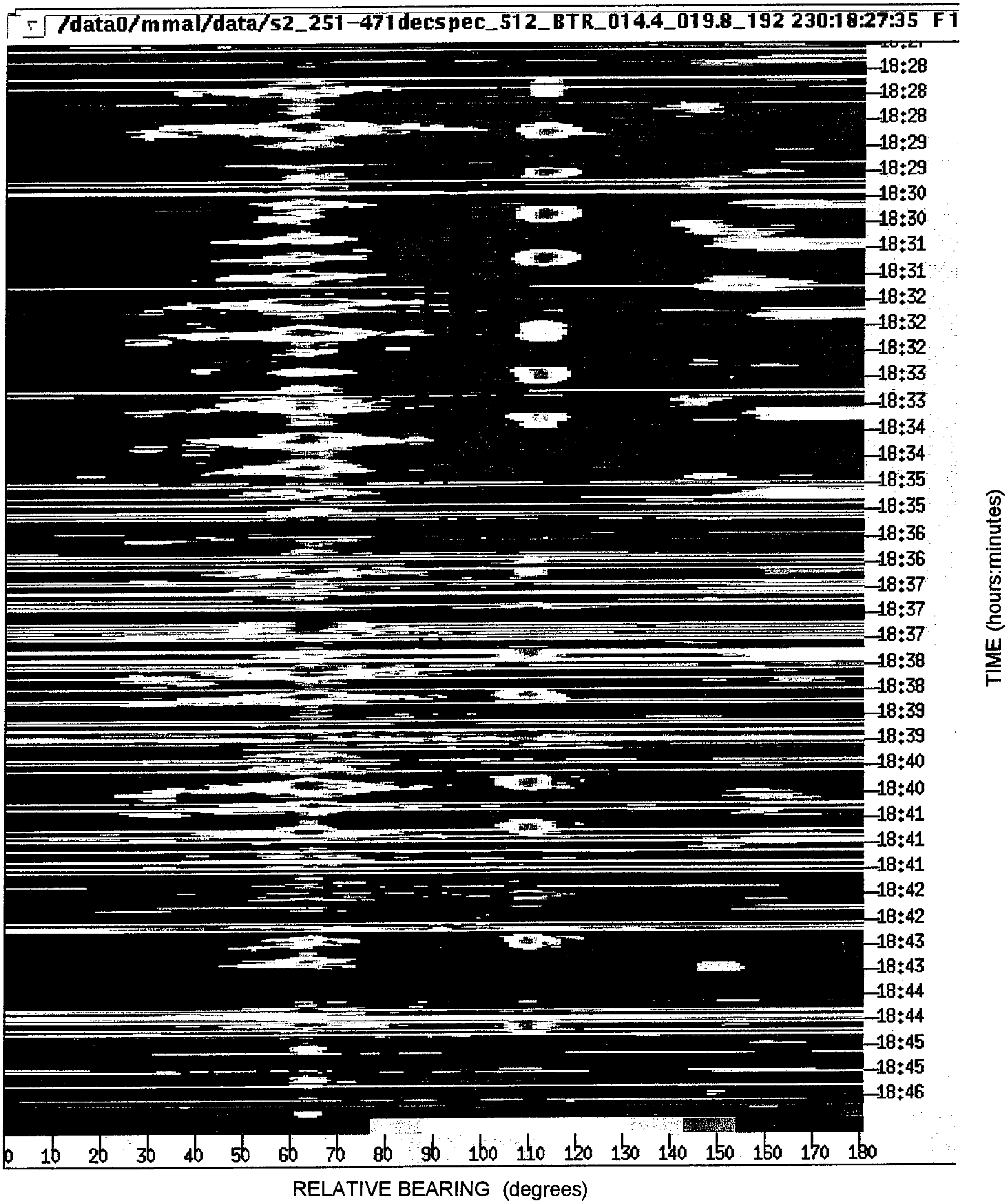

Figure 26. BTR of blue whales 1 and 2, 14.4- to 19.8-Hz band, tape S2_2, 181827Z, August 1994.

Table 3. Blue whale 1 (Beam 136) vocalization and ping summary.

VOCALIZATION START TIME (ZULU)	TRILL (SEC)	BREAK (SEC)	CHIRP (SEC)	BREAK (SEC)	PING START TIME (ZULU)
16:07:40	20	29	18	168	
16:11:35	22	33	20	52	16:11:57
16:13:42	25	28	19	56	
16:15:50	25	25	19	56	
16:17:55	24	28	18	60	
16:20:05	20	30	18	53	16:19:58
16:22:06	26	28	16	59	
16:24:37	22	28	12	164	16:27:58
16:27:41	30	22	18	52	
16:29:43	25	32	20	55	
16:31:51	22	30	20	52	
16:33:55	23	30	20	58	
16:36:06	22	28	24	53	16:35:56
16:38:13	20	33	24	129	
16:41:38	25	25	23	60	
16:43:52	20	30	23	57	16:43:43
16:46:02	25	27	20	55	
16:48:08	25	27	20	88	
16:50:48	27	27	18	57	16:51:43
16:53:08	23	26	20	60	
16:55:18	27	20	23	157	
16:59:05	20	22	25	60	16:59:59
17:28:06	20	32	15	64	
17:30:18	22	30	15	60	17:31:59
17:32:24	22	30	15	63	
17:34:34	22	30	17	70	
17:36:53	23	28	18	62	
17:39:04	22	28	18	154	17:39:58
17:42:46	20	28	----	----	
17:47:00	23	32	17	57	17:47:57
17:49:09	22	29	18	646	
18:01:09	22	28	17	142	17:55:57
18:04:43	23	----	----	----	
18:08:37	23	30	17	55	18:03:58
18:10:47	25	28	15	62	18:11:57
18:12:57	25	27	18	157	
18:16:44	32	17	18	58	
18:18:49	23	27	17	55	18:19:57
18:20:51	25	30	18	----	
mean & std. dev.	23.4 ± 2.7	27.9 ± 3.4	18.7 ± 2.8		

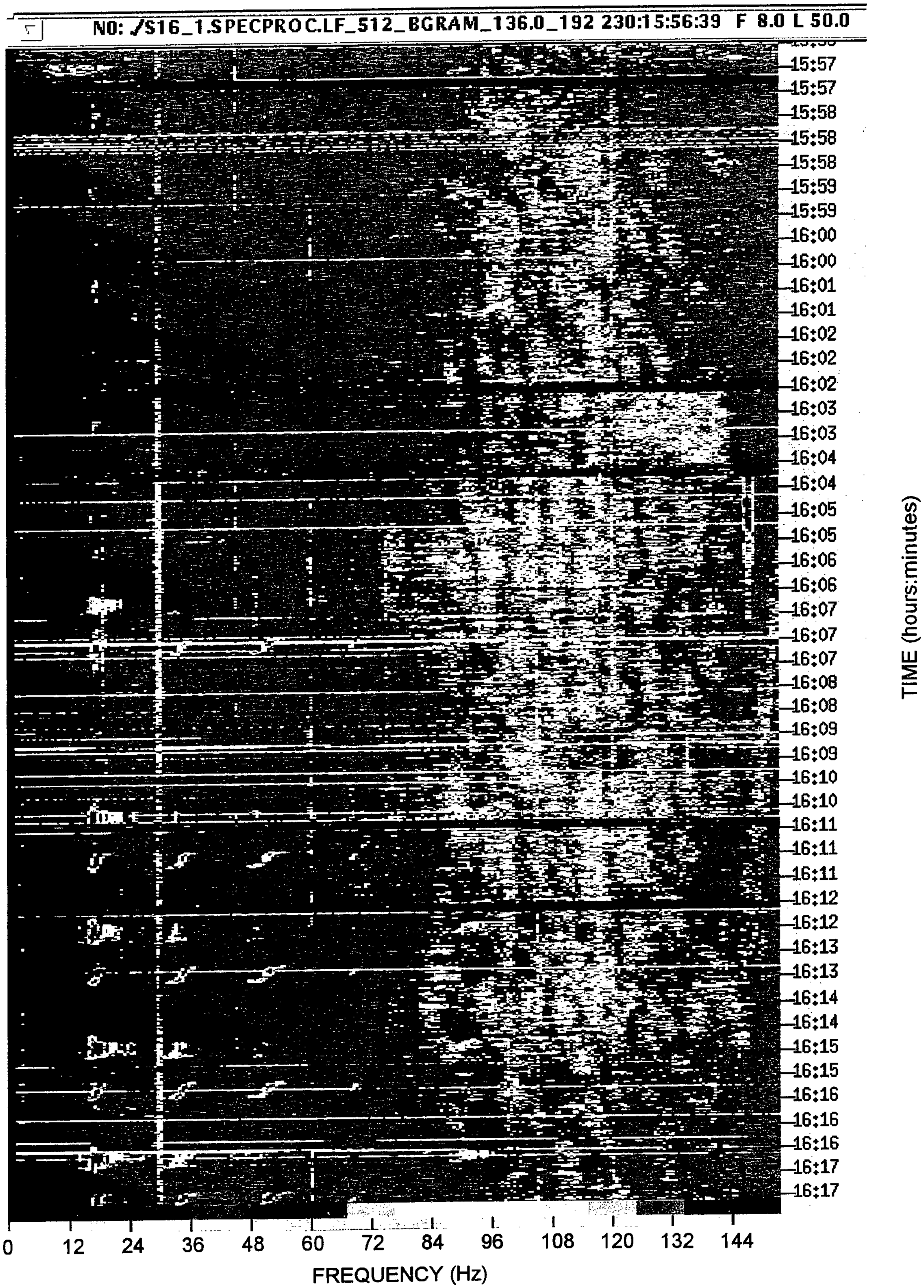

Figure 27. Gram of blue whale 1 (Beam 136), tape S16_1, 181557z, August 1994.

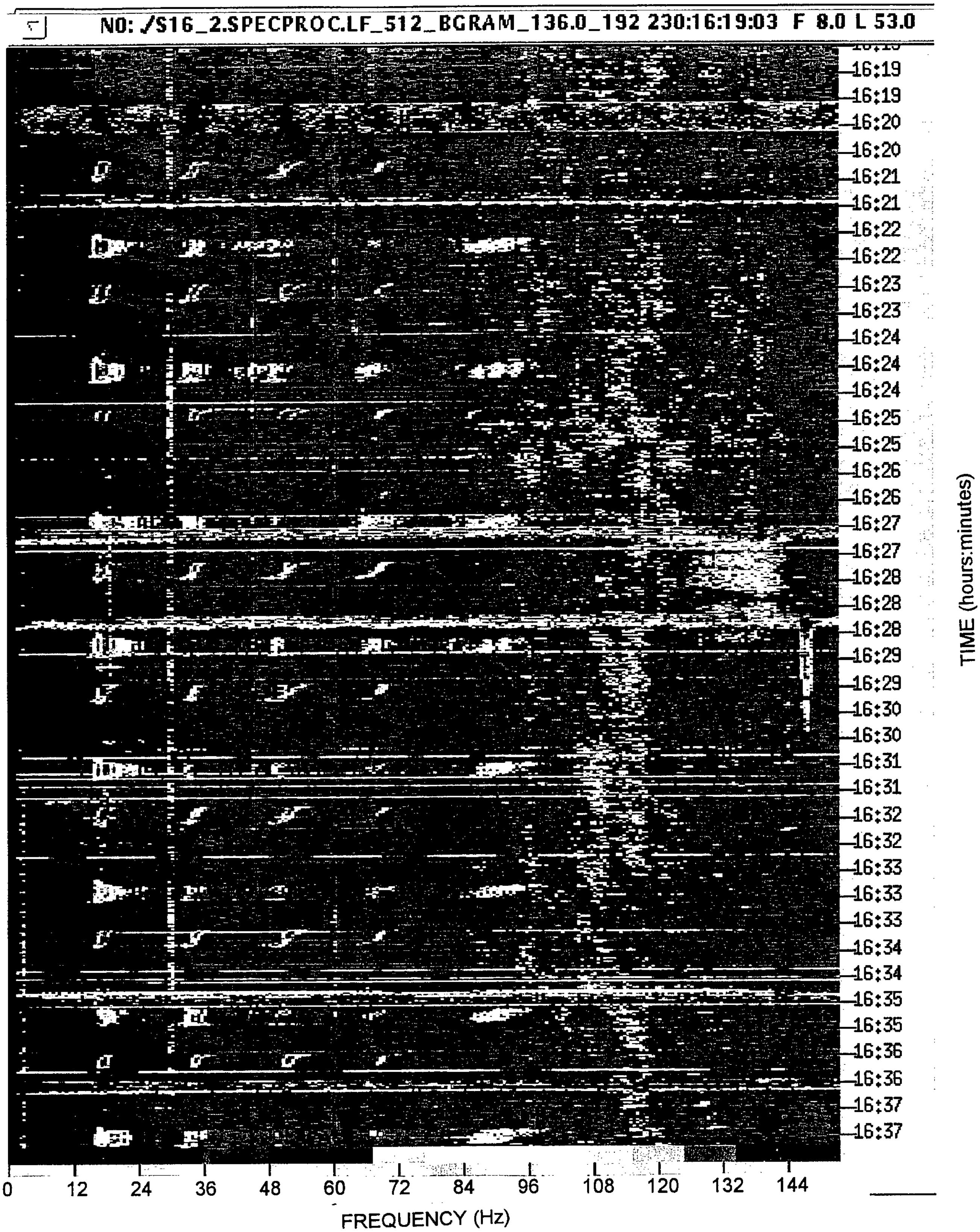

Figure 28. Gram of blue whale 1 (Beam 136), tape S16_2, 181619z, August 1994.

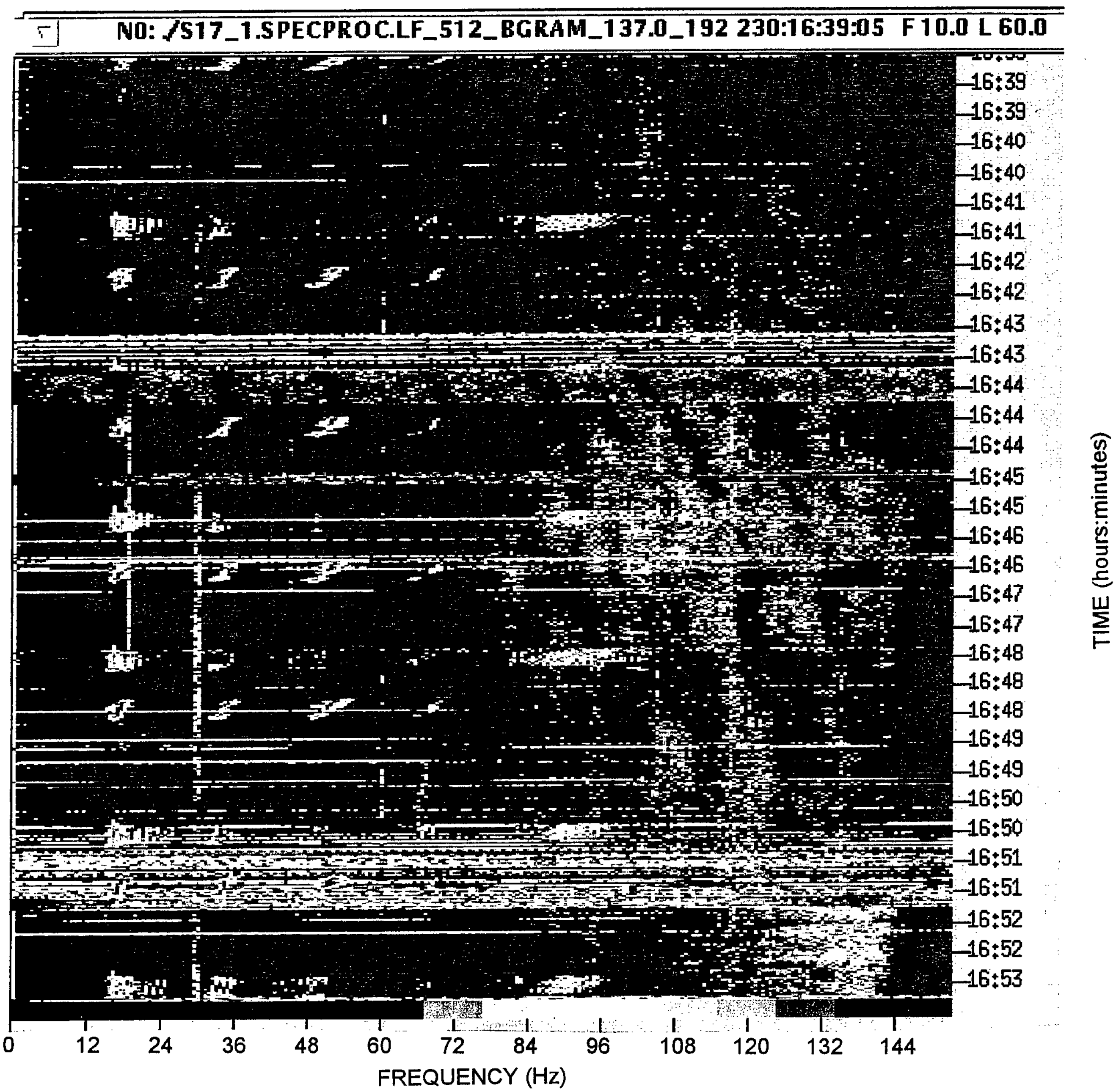

Figure 29. Gram of blue whale 1 (Beam 137), tape S17_1, 181639z, August 1994.

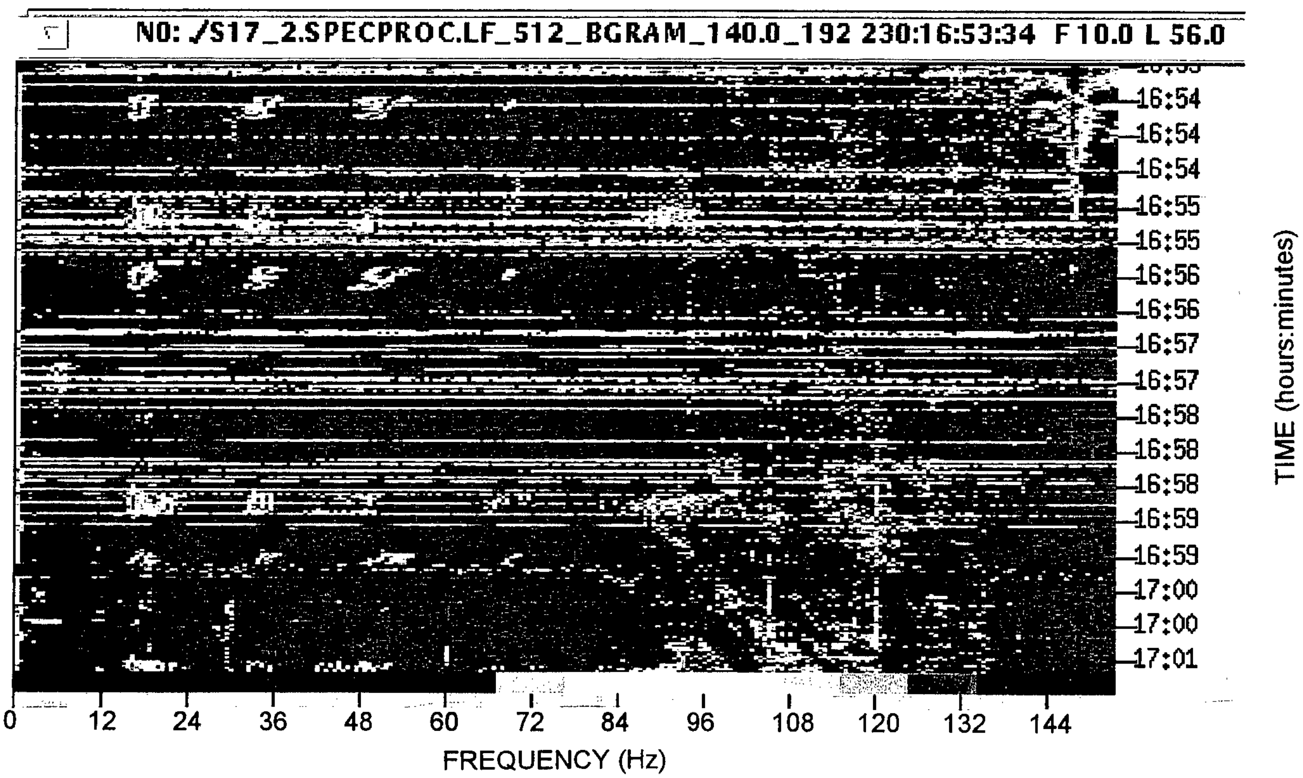

Figure 30. Gram of blue whale 1 (Beam 140), tape S17_2, 181654z, August 1994.

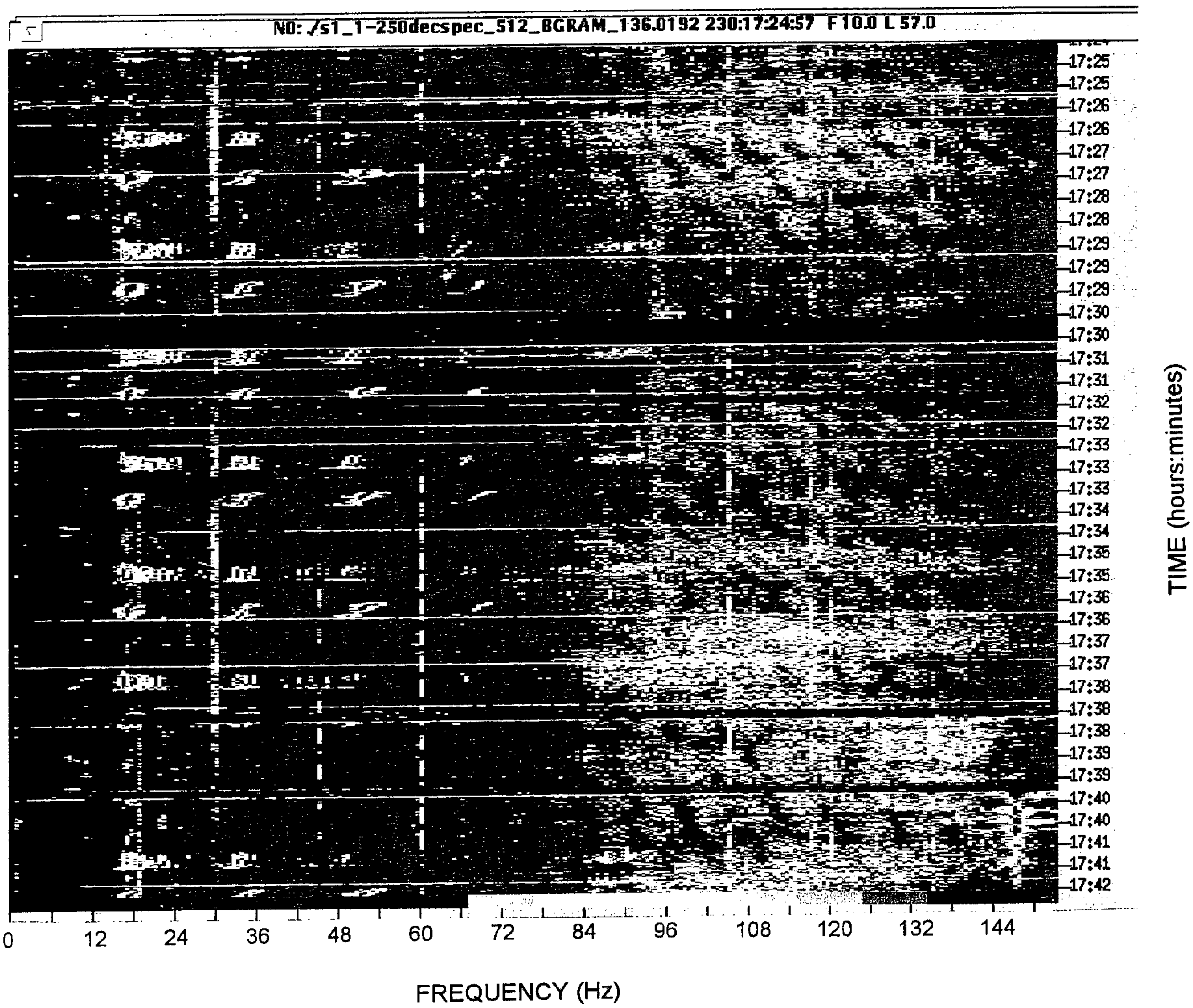

Figure 31. Gram of blue whale 1 (Beam 136), tape S1_1, 181725z, August 1994.

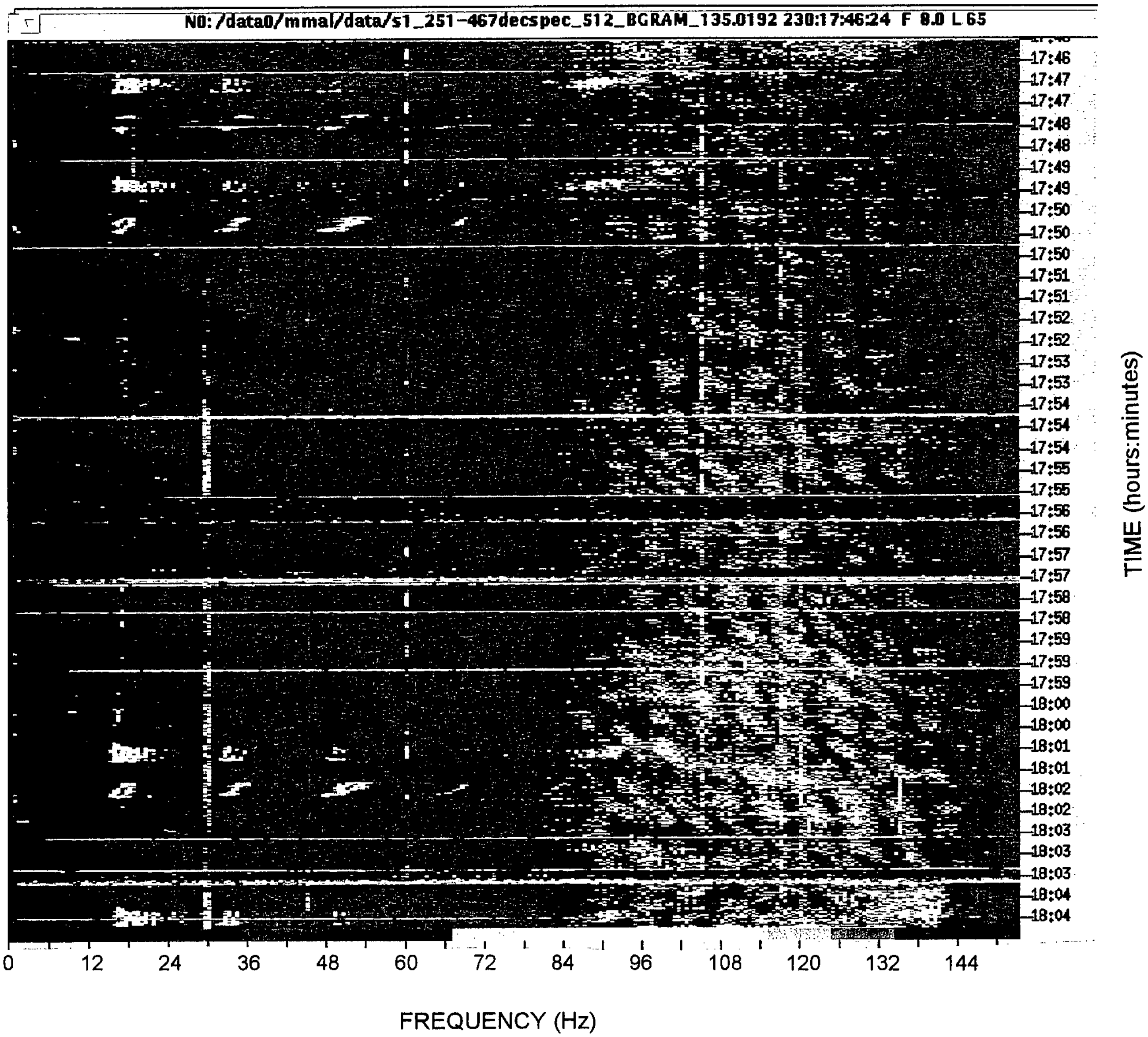

Figure 32. Gram of blue whale 1 (Beam 135), tape S1_2, 181746z, August 1994.

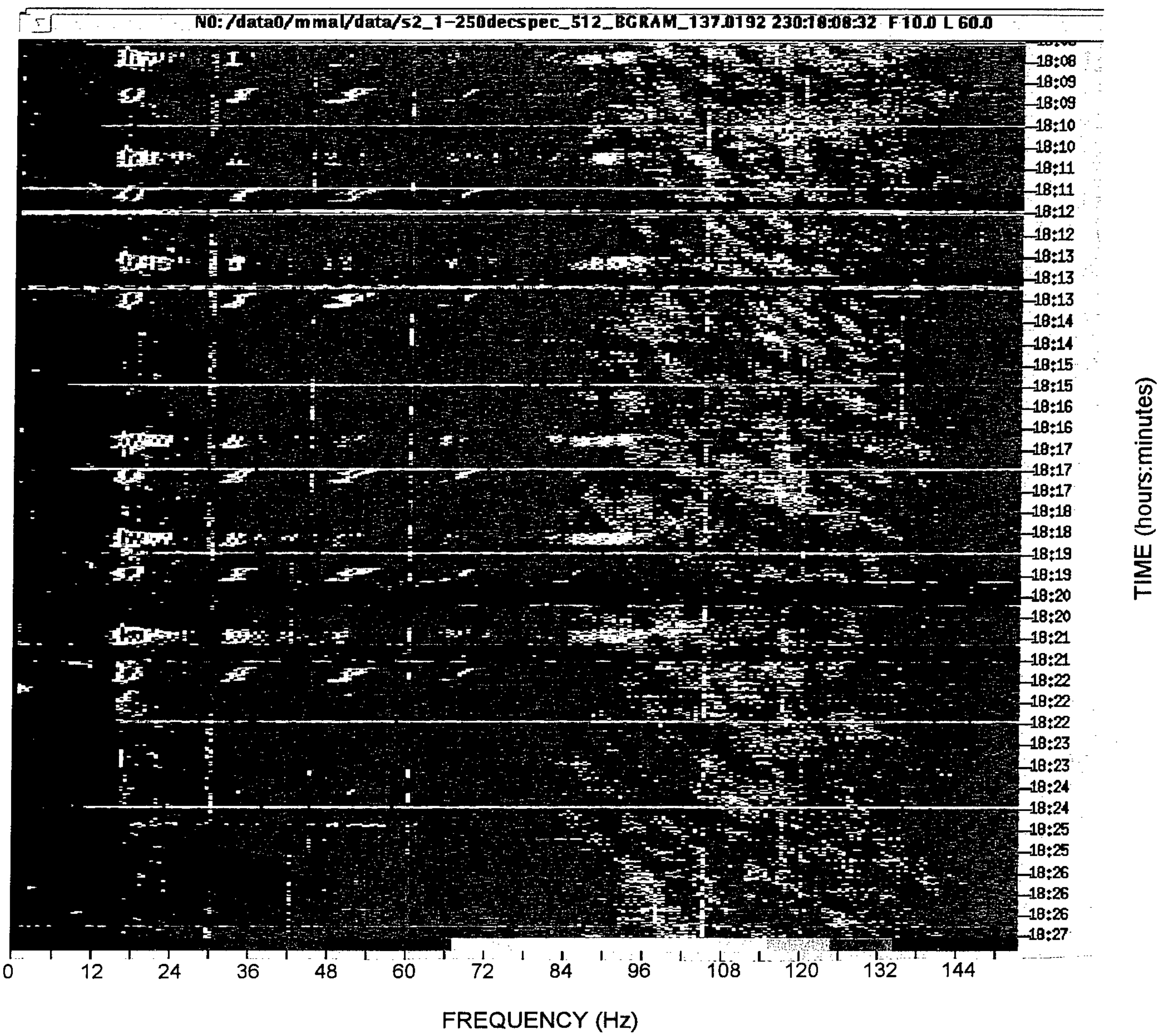

Figure 33. Gram of blue whale 1 (Beam 137), tape S2_1, 181808z, August 1994.

Table 4. Blue whale 2 (Beam 121) vocalization and ping summary.

Vocalization Start Time (zulu)	Chirp (sec)	Break (sec)	Trill (sec)	Break (sec)	Ping Start Time (zulu)
16:58:50	—	—	28	25	16:59:59
17:00:28	22	25	—	—	
17:27:24	17	32	—	—	
17:28:13	15	30	—	—	
17:28:58	17	30	—	—	
17:29:46	18	78	—	—	
17:31:23	—	—	20	74	17:31:59
17:32:56	17	30	—	—	
17:33:43	15	125	—	—	
17:36:03	—	—	23	23	
17:36:49	18	25	—	—	
17:37:33	18	32	—	—	
17:38:24	17	28	—	—	
17:39:09	18	30	—	—	
17:39:58	17	32	—	—	17:39:58
17:40:46	15	27	—	—	
17:41:31	17	33	—	—	
17:42:21	15	33	—	—	
17:43:09	15	—	—	—	
17:46:54	15	30	—	—	
17:47:39	13	33	—	—	17:47:57
17:48:25	18	30	—	—	
17:49:12	17	55	—	—	
17:50:24	—	—	23	32	
17:51:19	15	30	—	—	
17:52:04	15	32	—	—	
17:52:51	15	30	—	—	
17:53:36	17	180	—	—	
17:56:57	17	27	—	—	17:55:57
17:57:41	17	30	—	—	
17:58:27	17	30	—	—	
17:59:14	15	32	—	—	

Table 4. Blue whale 2 (Beam 121) vocalization and ping summary (continued).

Vocalization Start Time (zulu)	Chirp (sec)	Break (sec)	Trill (sec)	Break (sec)	Ping Start Time (zulu)
18:00:01	15	32	—	—	
18:00:47	17	55	—	—	
18:01:59	—	—	25	50	
18:02:54	17	23	—	—	
18:03:34	17	30	—	—	18:03:58
18:04:26	17	—	—	—	
18:09:15	13	32	—	—	
18:10:00	15	28	—	—	
18:10:44	17	30	—	—	
18:11:30	13	32	—	—	18:11:57
18:12:16	15	33	—	—	
18:13:04	13	57	—	—	
18:14:14	—	—	23	30	
18:15:07	17	30	—	—	
18:15:54	17	30	—	—	
18:16:41	17	30	—	—	
18:17:27	17	62	—	—	
18:18:46	—	—	20	27	
18:19:32	17	187	—	—	18:19:57
18:22:56	—	—	23	30	
18:23:49	13	33	—	—	
18:24:36	13	33	—	—	
18:25:22	13	32	—	—	
18:26:07	15	32	—	—	
18:26:54	15	32	—	—	18:27:57
18:28:08	—	—	20	28	
18:28:57	15	33	—	—	
18:29:45	10	30	—	—	
18:30:30	15	30	—	—	
18:31:15	17	55	—	—	
18:32:27	—	—	23	28	
18:33:19	15	32	—	—	

Table 4. Blue whale 2 (Beam 121) vocalization and ping summary (continued).

Vocalization Start Time (zulu)	Chirp (sec)	Break (sec)	Trill (sec)	Break (sec)	Ping Start Time (zulu)
18:34:06	15	134	----	----	18:35:52
18:36:34	----	----	15	32	
18:37:21	15	32	----	----	
18:38:08	15	30	----	----	
18:38:53	15	----	----	----	
mean & std. dev.	15.8 ± 1.8	30.4 ± 2.3	22.0 ± 3.3	34.4± 14.9	

obscured the subsequent chirp (see discussion below). There was no discernible disruption to the vocalization pattern created by the 10 active transmissions that occurred in this interval.

The beam grams associated with blue whale 2 are shown in figures 34 to 38. As was the case with blue whale 1, several of the blue whale 2 vocalizations overlap or are in close proximity to pings. In figure 35 for example, chirps 11 and 13 occur almost simultaneously with an active transmission, resulting in no discernible alteration to the pattern of chirps in the sequence.

Also in figure 35, amplifier clipping caused by the active transmission has probably obscured the first chirp that followed the first trill since the first chirp that can be observed occurs about 74 seconds later. This is the same interval that is found between the second trill and its second chirp and would explain the unusually long 74-second break between the first trill and first detectable chirp.

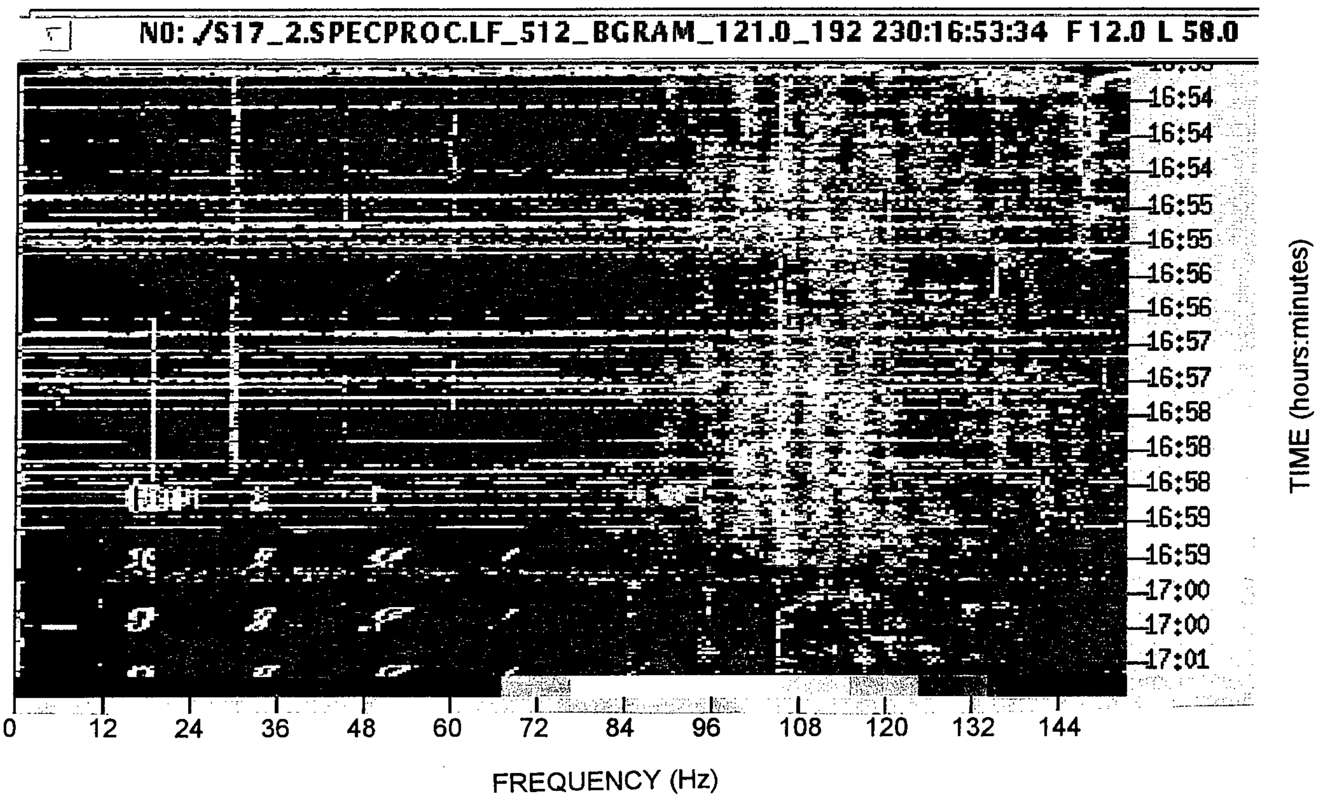

Figure 34. Gram of blue whale 2 (Beam 121), tape S17_2, 181654z, August 1994.

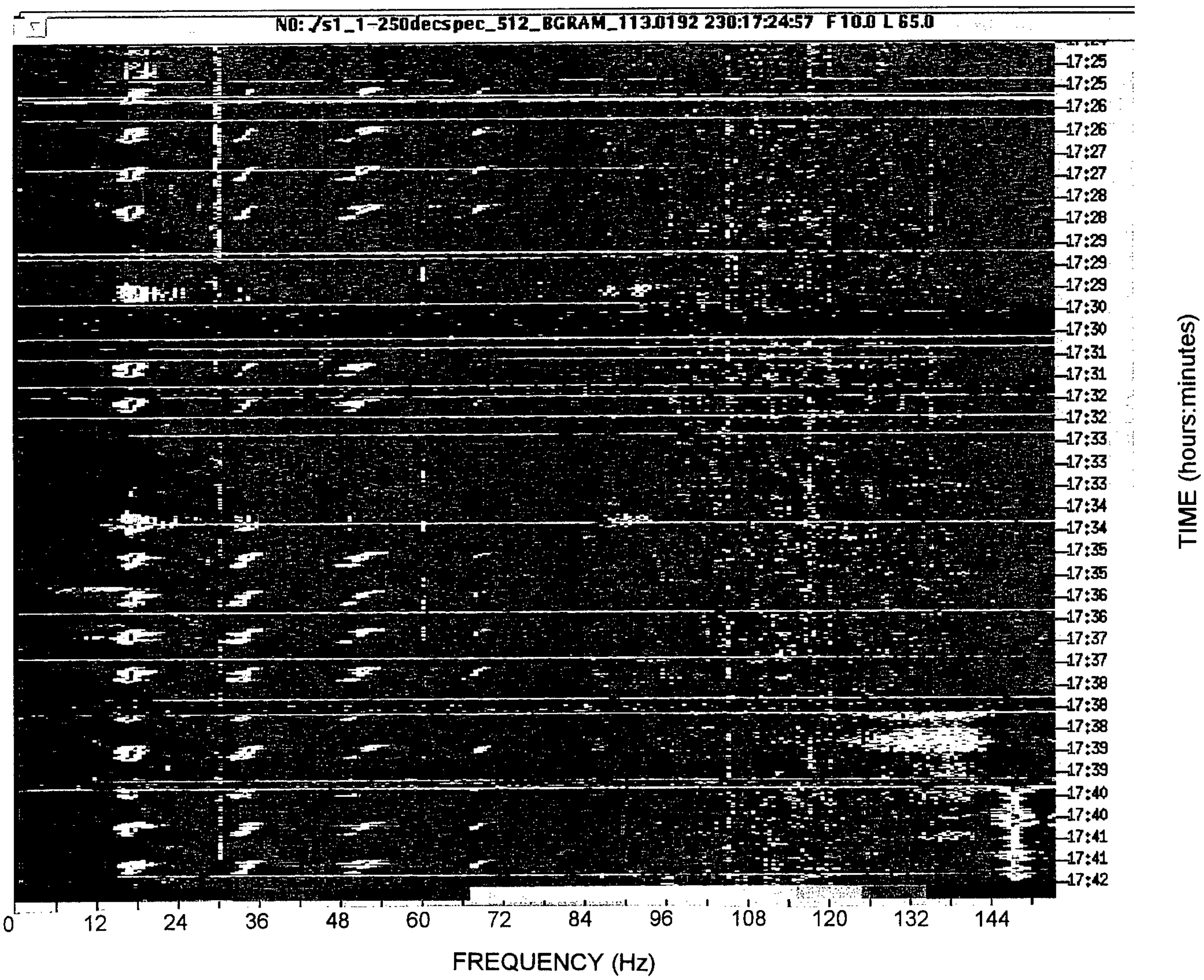

Figure 35. Gram of blue whale 2 (Beam 113), tape S1_1, 181725z, August 1994.

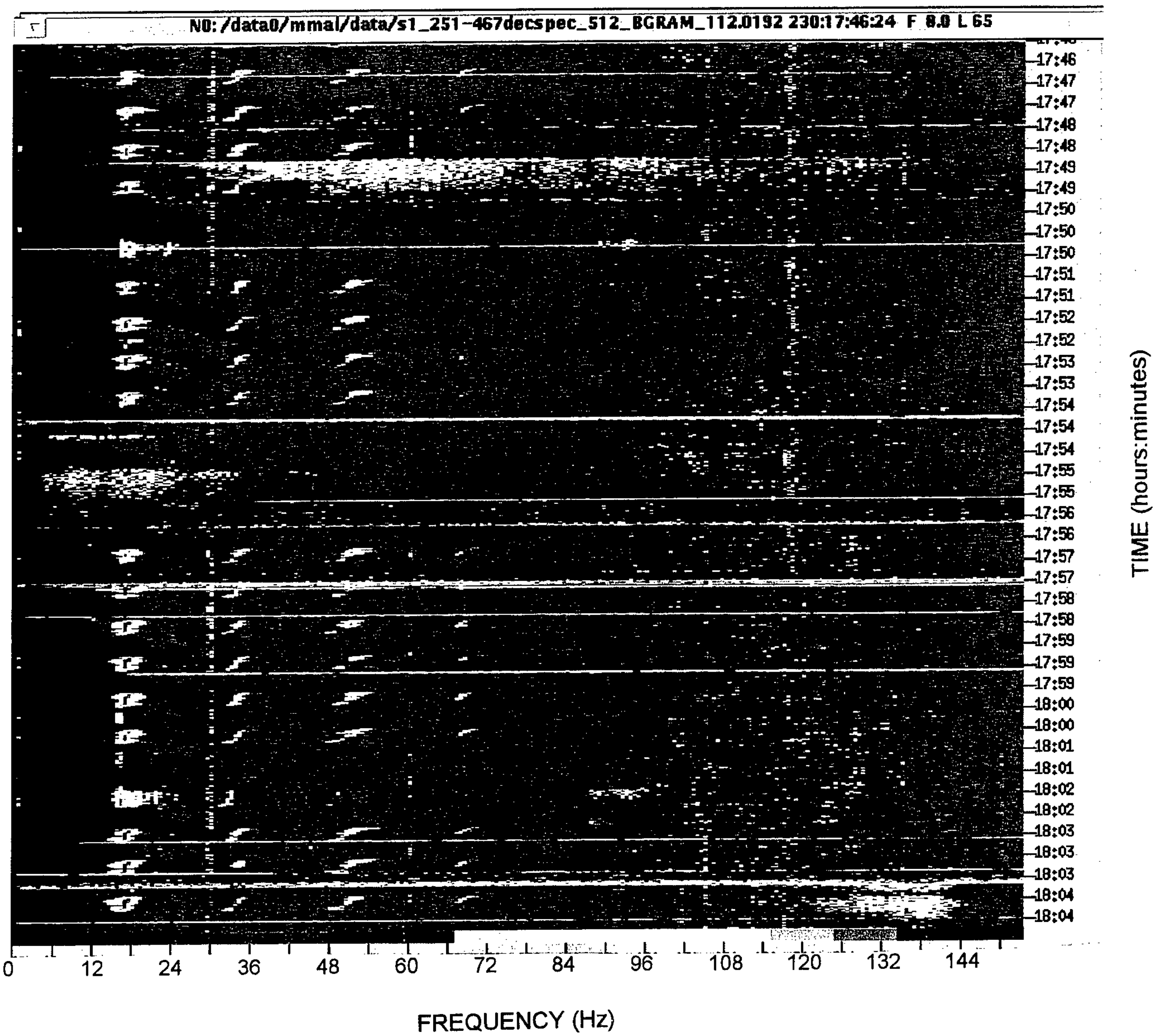

Figure 36. Gram of blue whale 2 (Beam 112), tape S1_2, 181746z, August 1994

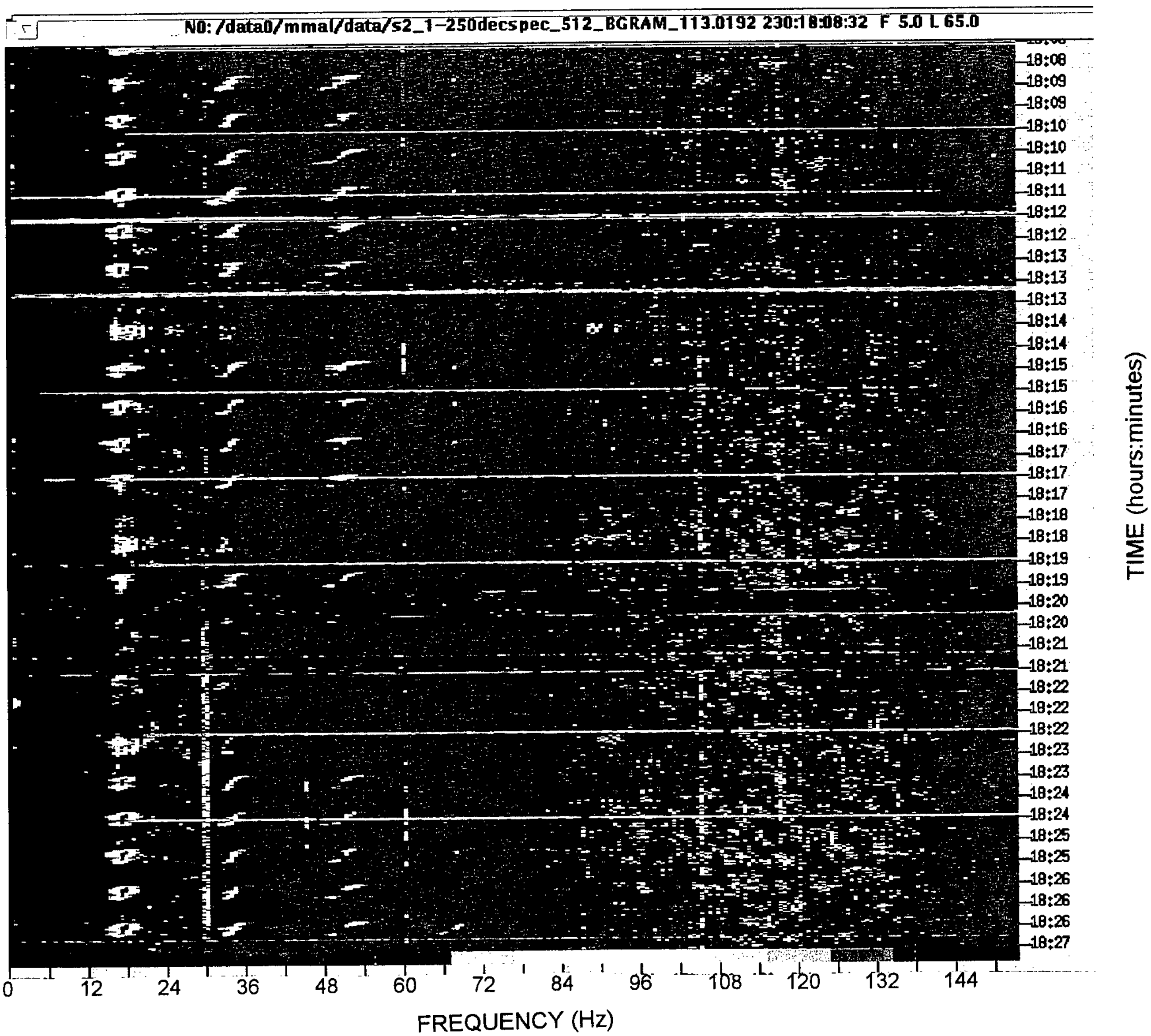

Figure 37. Gram of blue whale 2 (Beam 113), tape S2_1, 181808z, August 1994.

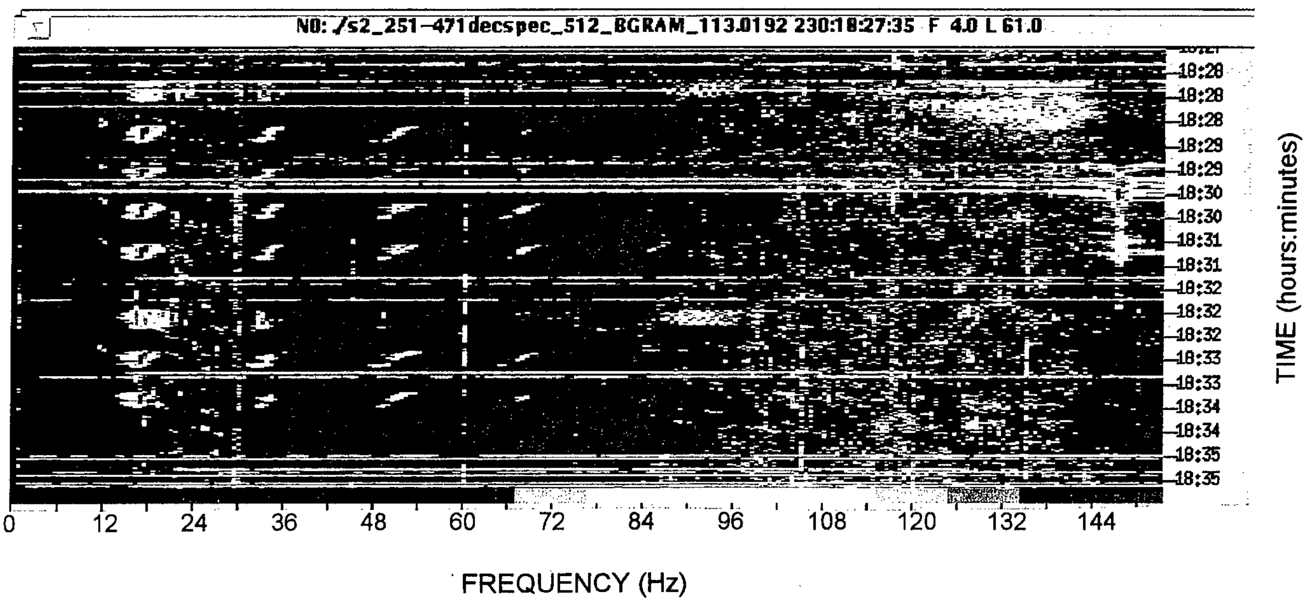

Figure 38. Gram of blue whale 2 (Beam 113), tape S2_2, 181827z, August 1994.

As can be seen in figure 36, blue whale 2 continues to vocalize with a series of chirps and occasional trills. There was one pause of about 3 minutes between chirps, but the pattern of chirps approximately every 30 seconds was otherwise maintained throughout the interval and not altered by any of the source transmissions. A portion of the 10th chirp occurred during a 10-second transmission with no apparent effect to its frequency characteristics or temporal spacing relative to the previous and subsequent chirps.

The now familiar vocalization pattern of blue whale 2, which consists of a series of chirps and an occasional trill can be seen in figure 37, as well. The first source transmission has no discernible effect on the pattern of vocalizations. The following transmission occurs during an extended 187-second break between a chirp and a trill. Such extended breaks between chirps and trills are common, so it is improbable that the source transmissions disrupted the pattern.

The beam gram of the data set that spanned the interval 18:27:35 to 18:46:36 is shown in figure 38. Due to the large number of data outages on the last portion of the acoustic tape, the quality of the data after 18:35:00 was significantly lower and was not shown in the figure or used in the analysis. There was one source transmission in this interval, and it appeared to have no effect on the duration or repetition rate of the whale vocalizations.

A BTR of several finback whale detections is shown in figure 39. Finbacks can be seen on several beams including beams 34, 40, 88, and 134. A gram of the finback on beam 134 is shown in figure 40. The finback vocalizations are of short duration (1 second) and vary in bandwidth and start frequency. The sequence shown is too short to enable a specific vocalization pattern to be determined and to evaluate the effect of the three source transmissions on those vocalizations. A large data set of finback vocalizations were recorded and a detailed analysis is planned for the future.

3.2.2 Range Measurement

The ranges of both blue whales from the active source were estimated from the cross fix obtained with the forward and aft subarray BTRs as discussed in section 3.1 and appendix B for the peak power in a band around the third harmonic (51 Hz) of the blue whale chirps. The range estimates for blue whales 1 and 2 using this method are plotted in figure 41. Each range estimate was determined from the mean forward and aft bearings for the duration of the signal (nominally 20 seconds for a chirp). There was significant variation between some estimates due to factors such as array motion, beam width resolution, and the relatively short distance (0.71 nmi) between the subarrays. These factors resulted in large range excursions that are not representative of actual range changes. The estimates plotted in figure 41 were smoothed by filtering those ranges that would have required the whales to achieve a speed in excess of 30 kts. The filtered mean ranges for blue whales 1 and 2 over the entire

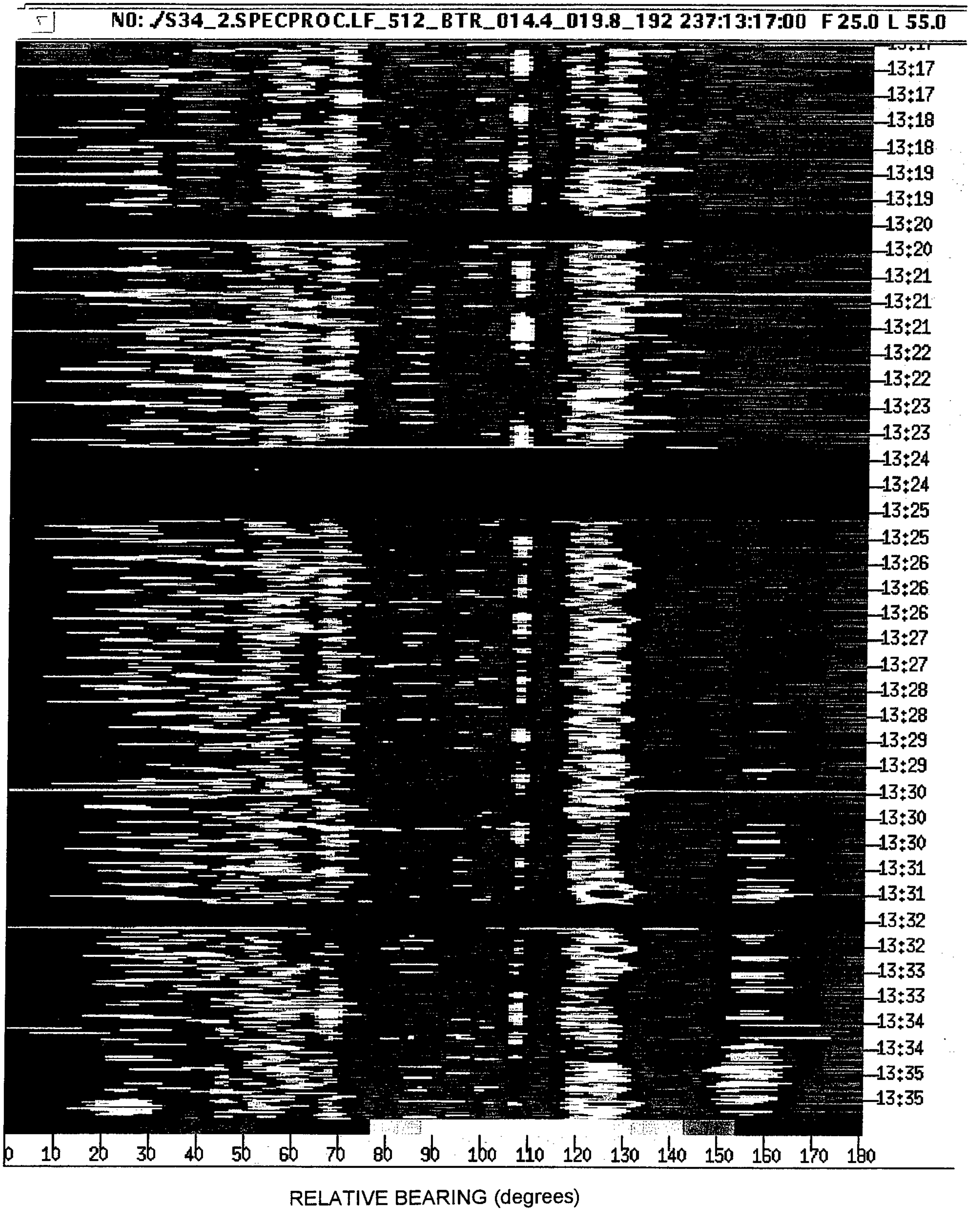

Figure 39. BTR of finback whales, 12-36 Hz band, tape S34_1, 251255z, August 1994.

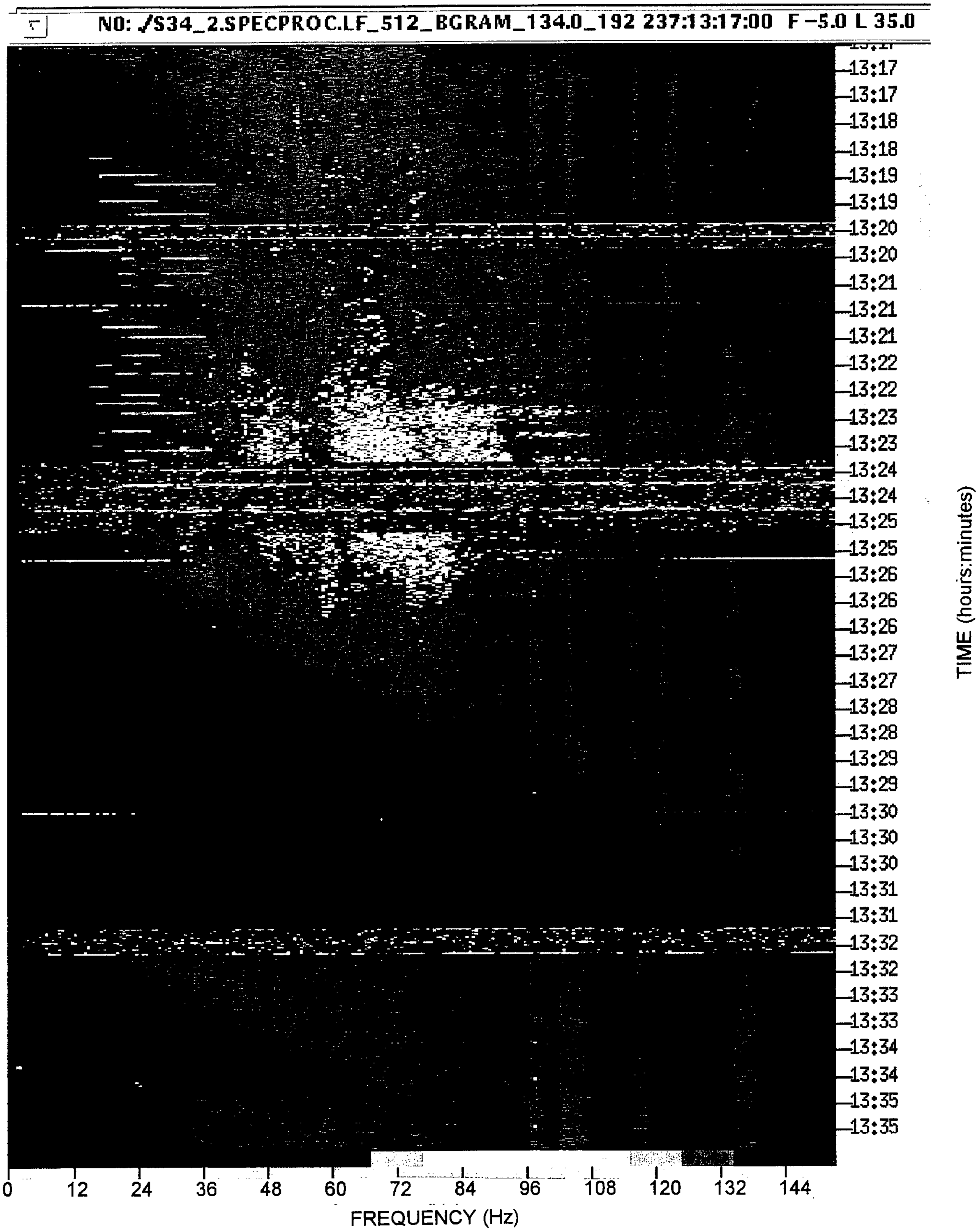

Figure 40. Gram of finback whale (Beam 134), tape S34_1, 251255z, August 1994.

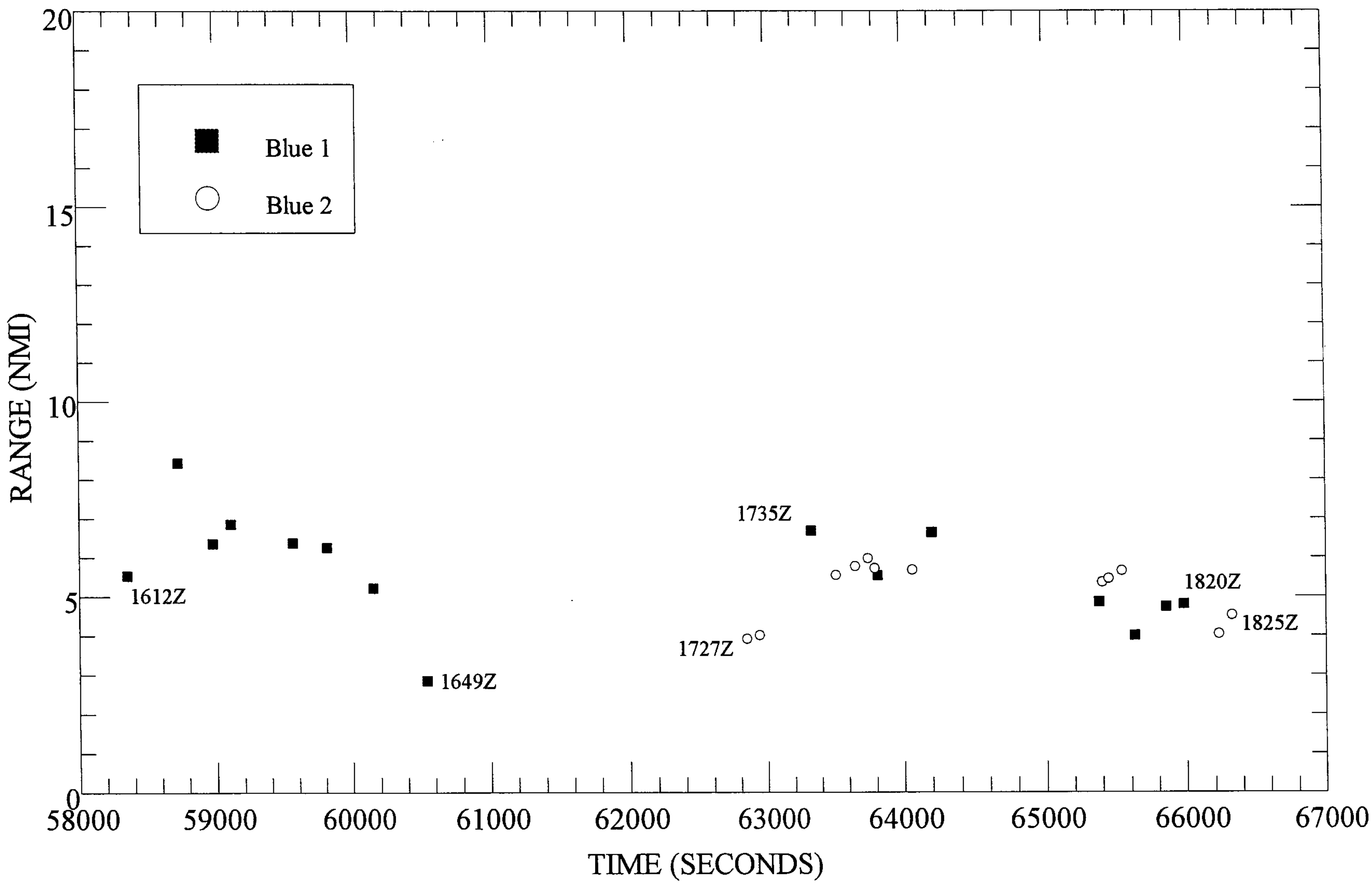

Figure 41. Range estimates of blue whales 1 and 2 from acoustic source.

observation interval were 5.67 ± 1.35 nmi and 5.14 ± 0.77 nmi, respectively. The tracks of the source ship (R/V-1) and blue whales 1 and 2 are plotted for the interval 1727Z to 1825Z for which R/V-1 position data were available in figure 42. Although the bearing ambiguity was not resolved, the whales were believed to be on the starboard beams as plotted.

3.2.3 RECIEVED ACTIVE SOURCE LEVELS AT THE WHALES

The received levels at the whales for three active transmissions were estimated based on the known source levels and the transmission loss (TL) calculated from both actual TL measurements and with a Parabolic Equation (PE) model. The TL measurements were conducted during the Magellan II Operations Preparation (OPS PREP), 6-12 July. The OPS PREP was performed in the same Southern California (SOCAL) shallow water region as the Segment 1 operations on 18 August. The July and August sound speed profiles were very similar and indicated that acoustic energy was refracted downward due to the steep temperature gradient of the surface layer. The August sound speed profiles obtained from the Segment 1 shallow water XBT and XSV measurements are plotted in figure 43. The measured TL for the tracks plotted in figure 44 is shown in figure 45. The TL was measured at source frequencies of 180, 227, and 286 Hz with a source depth of 300 feet and a receiver depth of 351 feet. As can be seen in the plot, the measured TL was 75 to 95 dB at 3- to 10-nmi ranges.

For comparison, TL was estimated with a PE model for three active transmissions along the radials that blue whale 1 was concurrently passively detected. The modeled TL is plotted as a function of range and depth in figures 46 to 51. A source frequency of 225 Hz and a depth of 250 feet were used for all the estimates. The TL at ranges of 4 to 10 nmi for a nominal depth of 100 feet were 70 to 85 dB for both the port and starboard bearings. Previous detections indicate that blue whale 1 was on the starboard side of the array, but both port and starboard TLs are shown since the ambiguity was not clearly resolved.

The detection ranges at the time of the three pings were approximately 5 nmi. The upper and lower TL limits yielded by both methods at this range were 70 to 85 dB. Thus, the received levels at the whale are estimated to have been 70 to 85 dB below the full transmit power of the source (source was transmitting at full power, uniform shading, for the three pings studied).

3.2.4 WHALE VOCALIZATION LEVELS

The whale vocalization levels can be estimated from their receive levels and the results of the range and TL measurements. The TL for the 17-Hz blue whale 1 fundamental was also estimated with the PE model. The TL was calculated along the same three radials as in the previous section and assuming that the whale was at a nominal depth of 100 feet. The modeled TL versus range

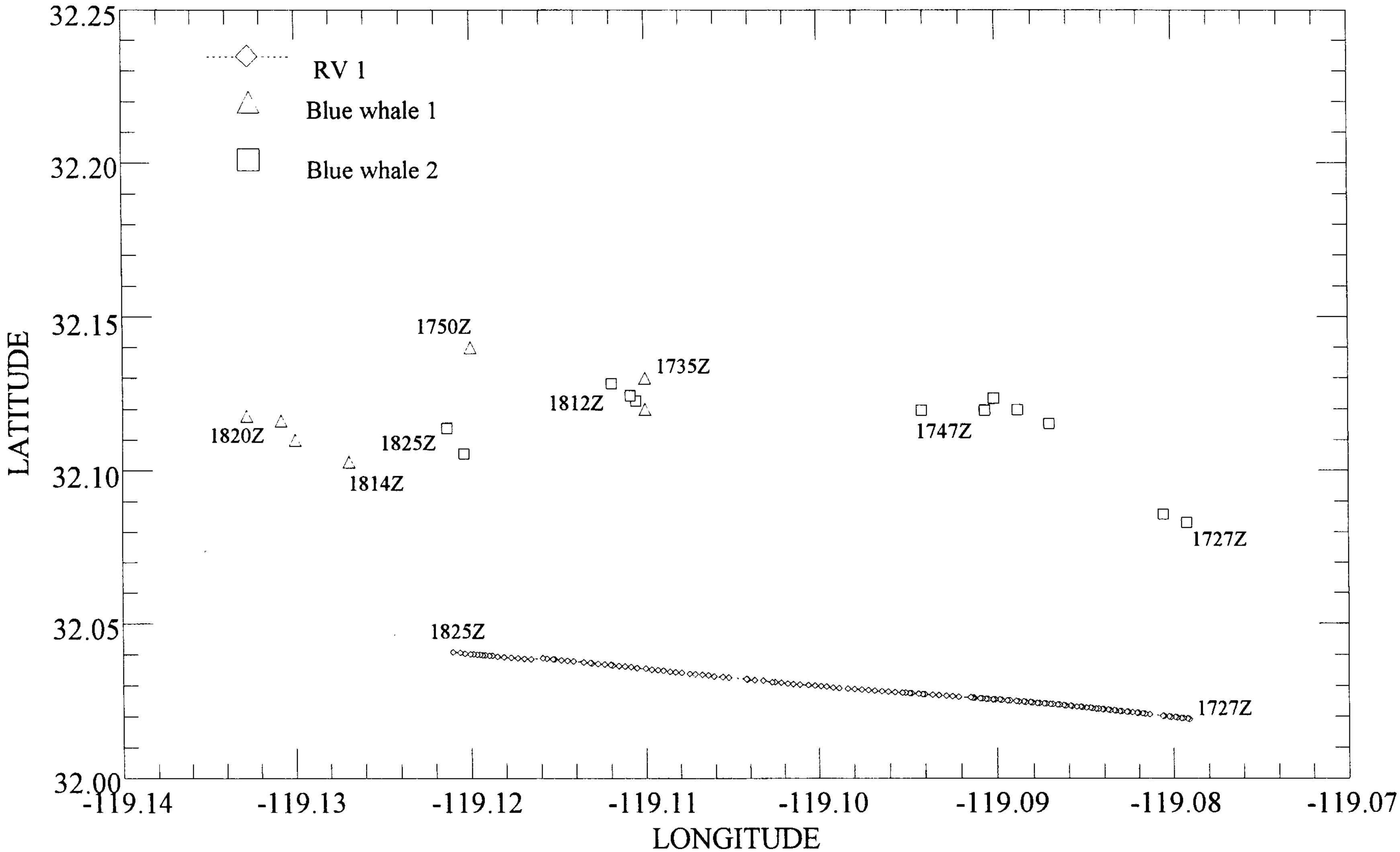

Figure 42. Tracks of acoustic source ship (R/V-1) and blue whales 1 and 2.

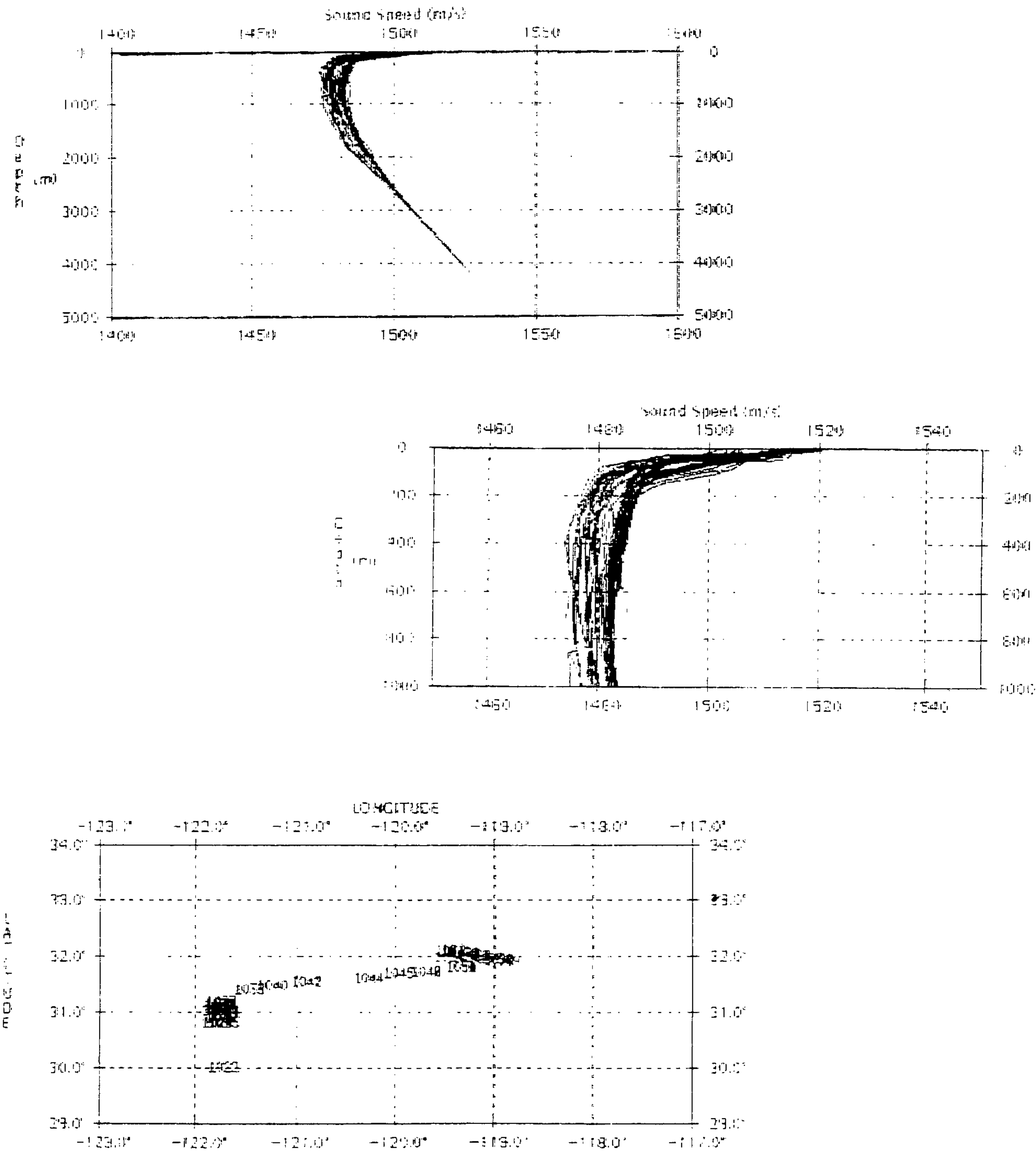

Figure 43. Sound speed profiles from Magellan II SOCAL shallow water OPAREA.

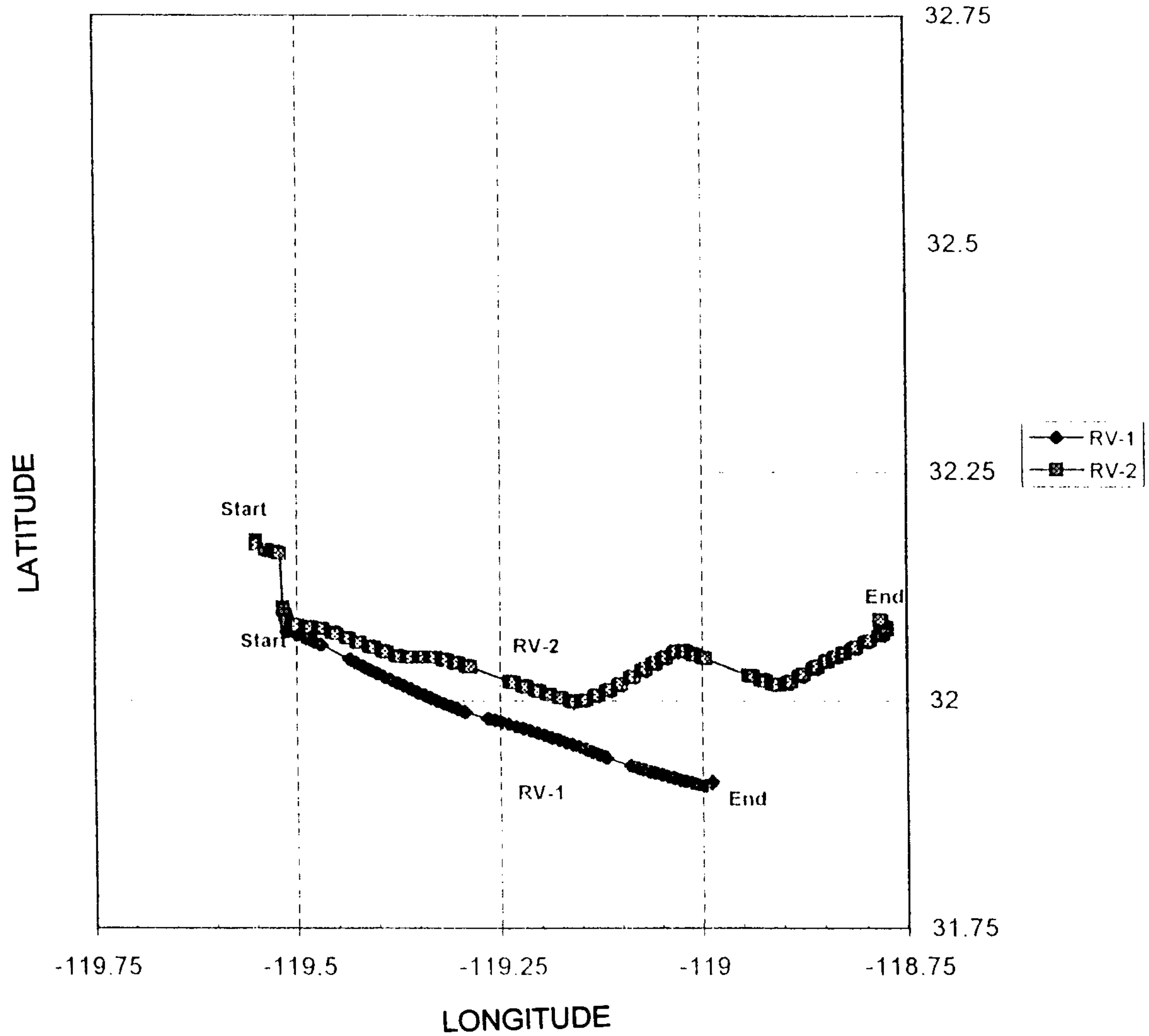

Figure 44. Source (R/V-2) and receiver (R/V-1) tracks for OPS PREP TL measurement.

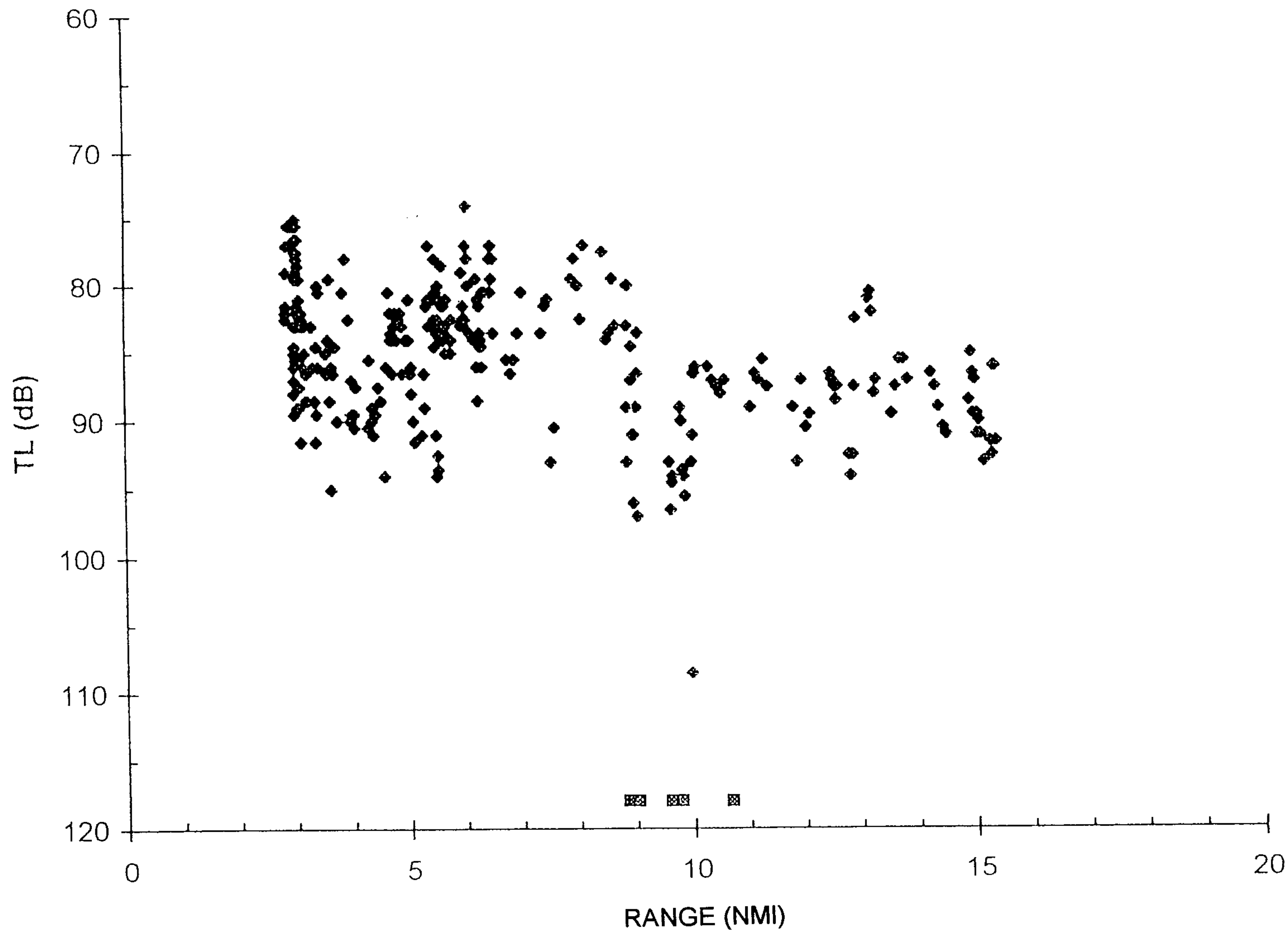

Figure 45. TL for OPS PREP track of figure 3-34.

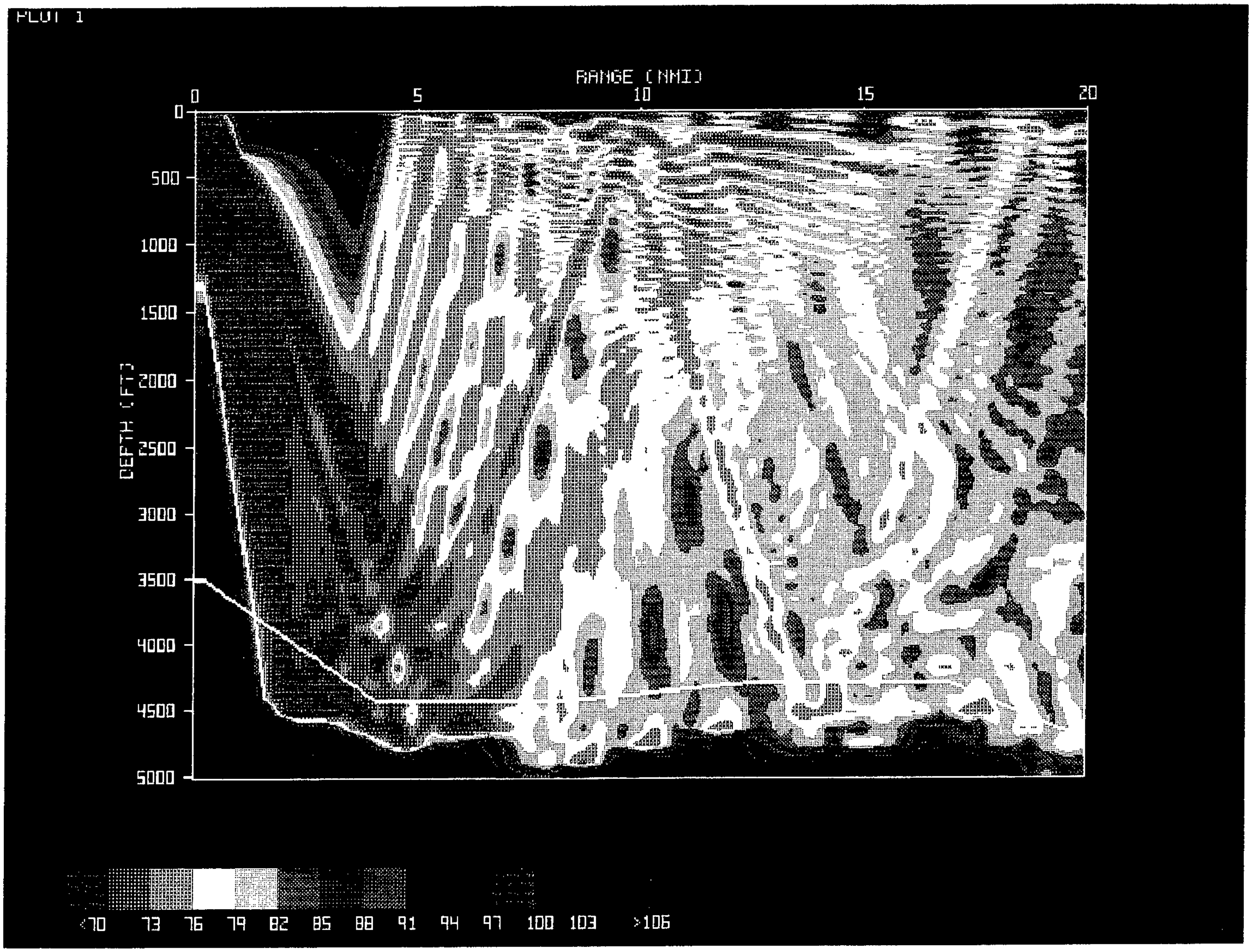

Figure 46. Modeled TL for 263° T radial, 225-Hz source at 250-ft depth, 181612Z August 1994.

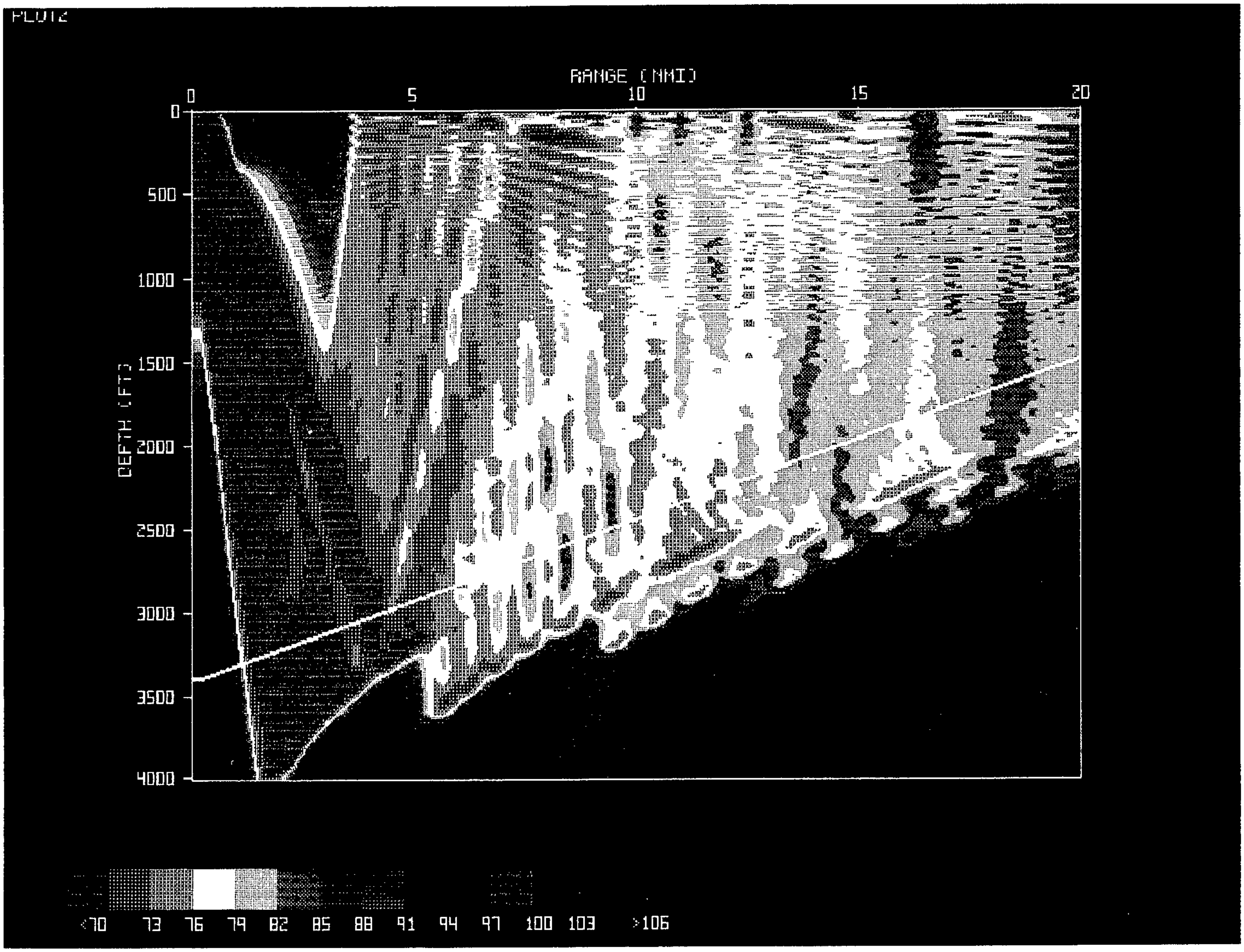

Figure 47. Modeled TL for 351° T radial, 225-Hz source at 250-ft depth, 181612Z August 1994.

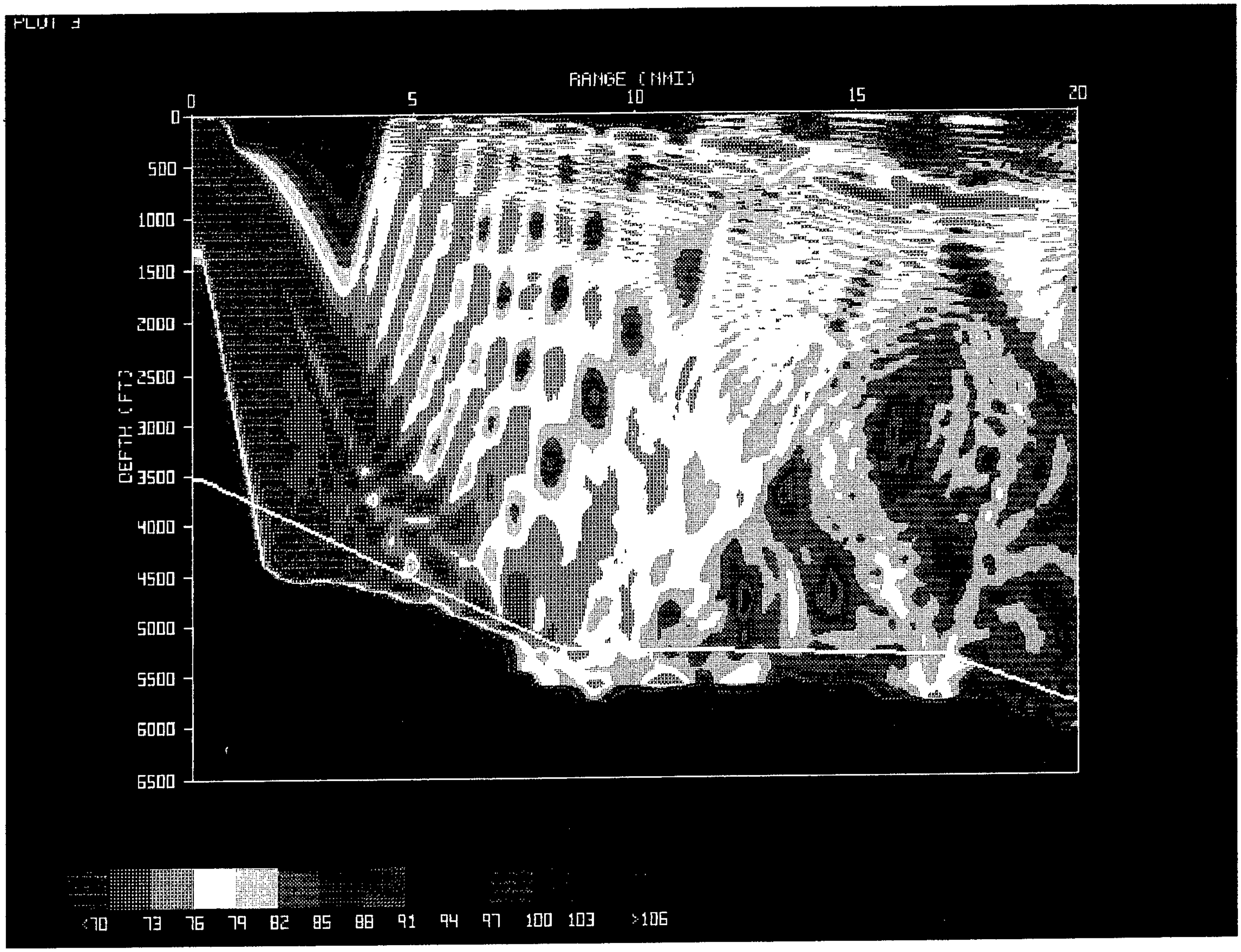

Figure 48. Modeled TL for 261.6° T radial, 225-Hz source at 250-ft depth, 181644Z August 1994.

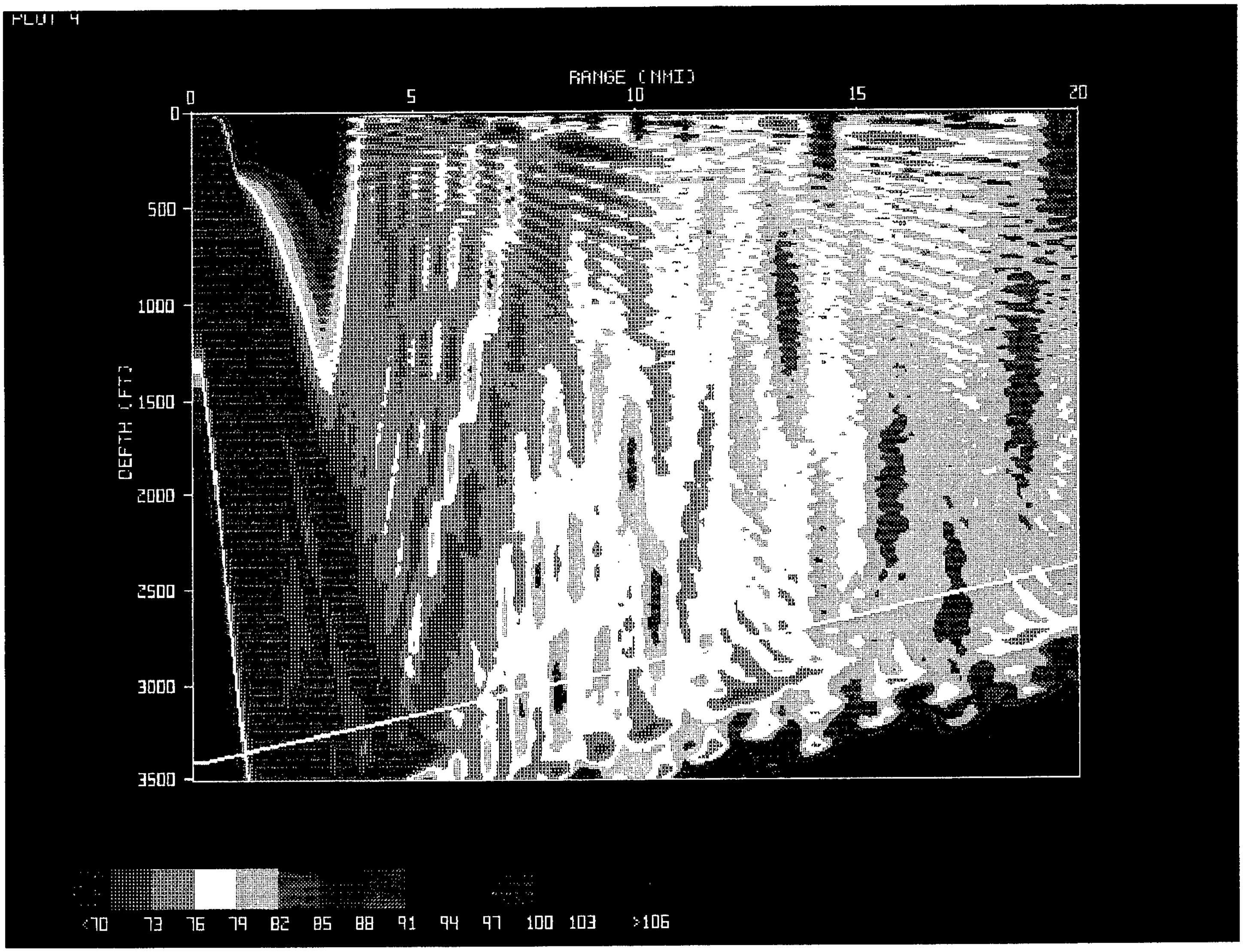

Figure 49. Modeled TL for 347.6° T radial, 225-Hz source at 250-ft depth, 181644Z August 1994.

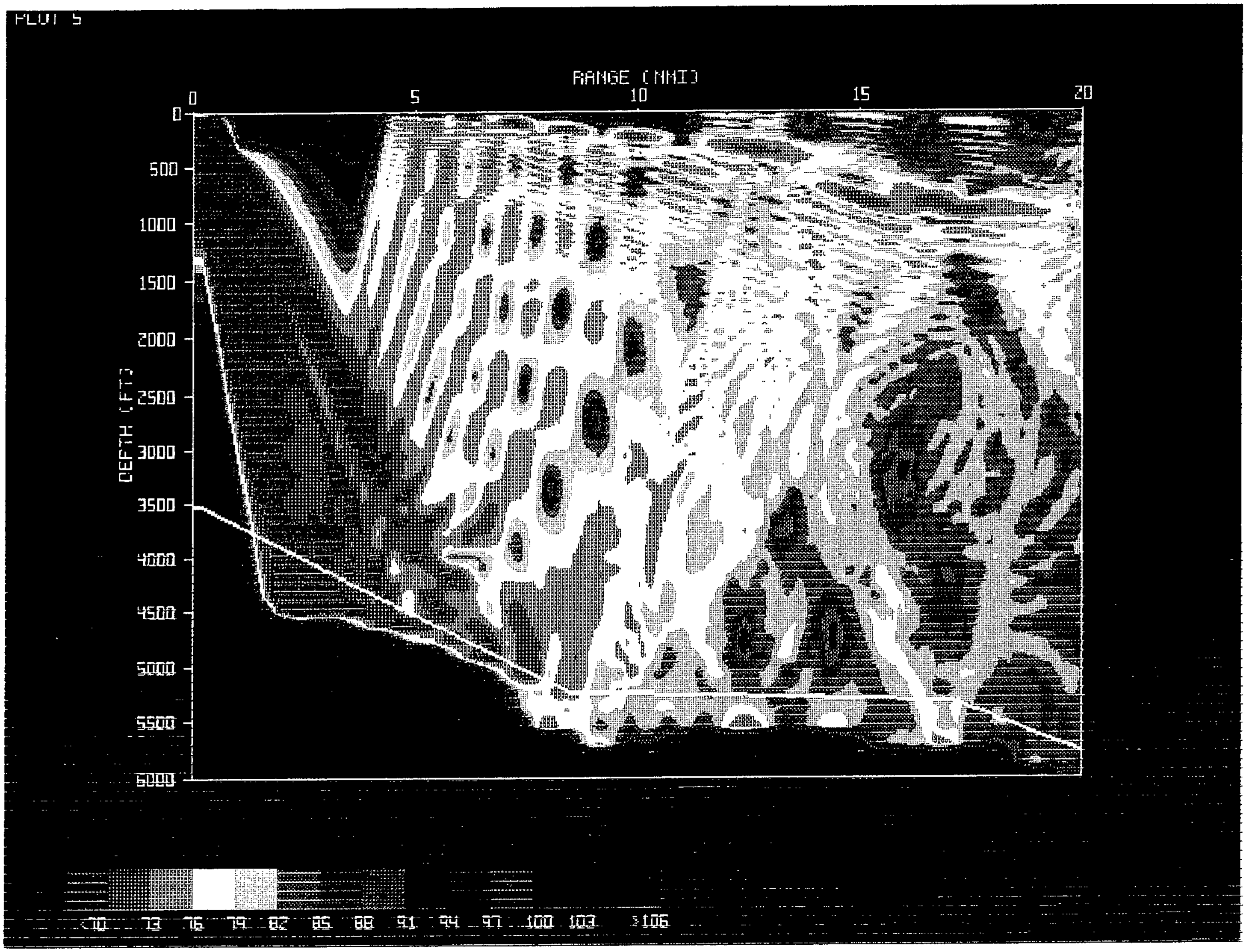

Figure 50. Modeled TL for 258.8° T radial, 225-Hz source at 250-ft depth, 181732Z August 1994.

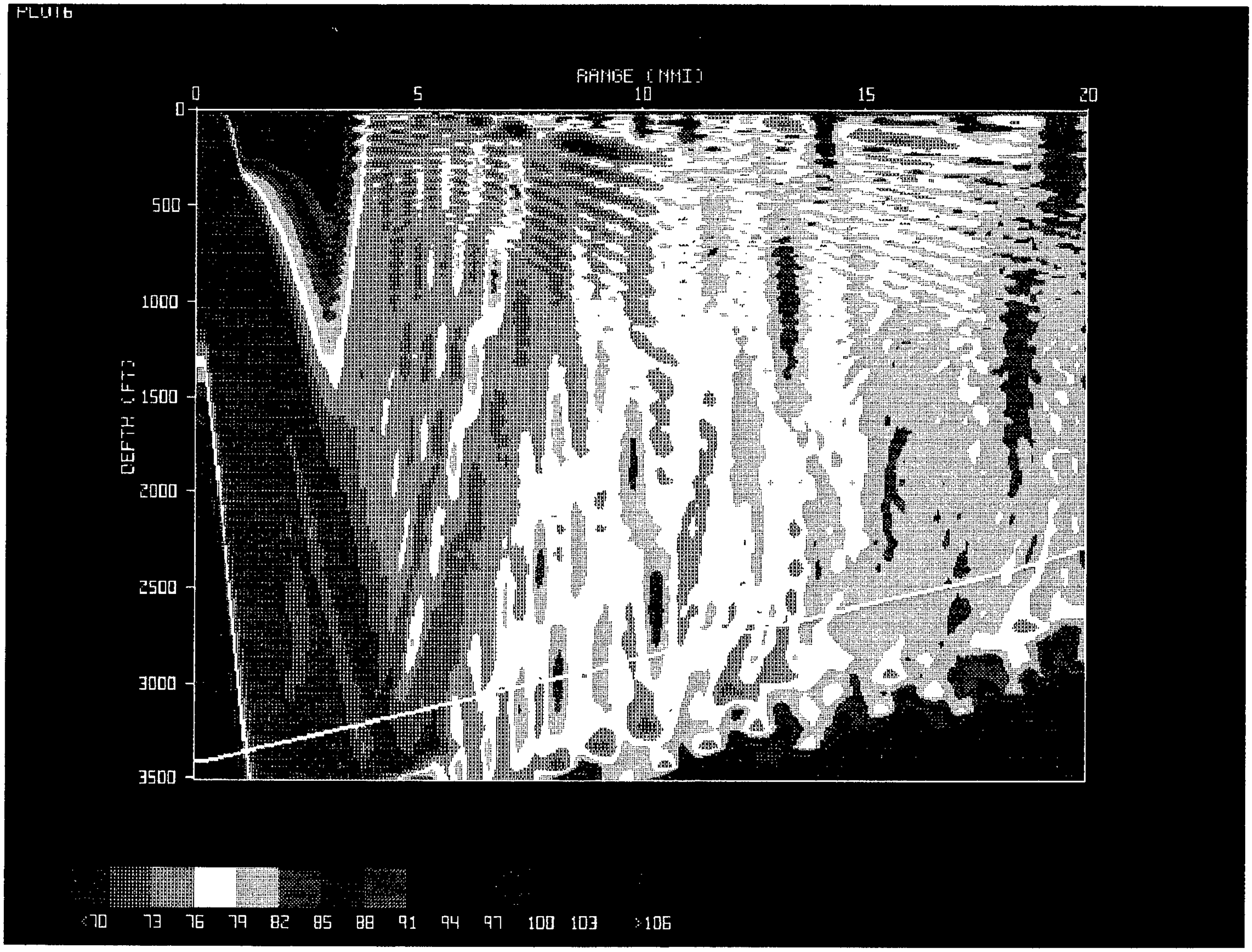

Figure 51. Modeled TL for 346.8° T radial, 225-Hz source at 250-ft depth, 181732Z August 1994.

and depth is plotted in figures 52 to 54. From the model estimates of the TL at the blue whale 1 detection ranges and the measured received levels of the 17-Hz blue whale 1 signal, the whale source levels were estimated and are summarized in table 5.

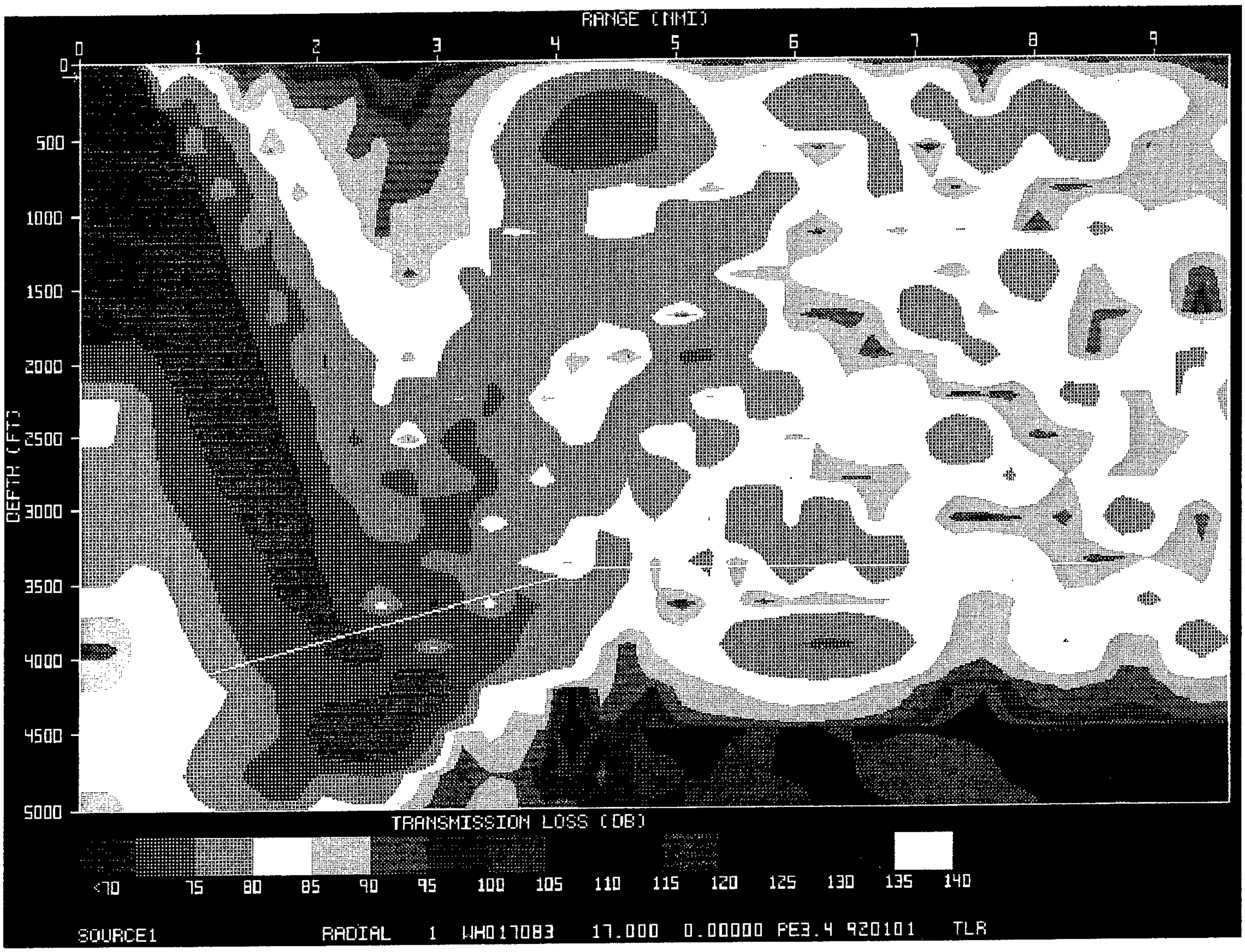

Figure 52. Modeled TL (whale to receive array) for 83° T radial, 17-Hz source at 100-ft depth, 181612Z August.

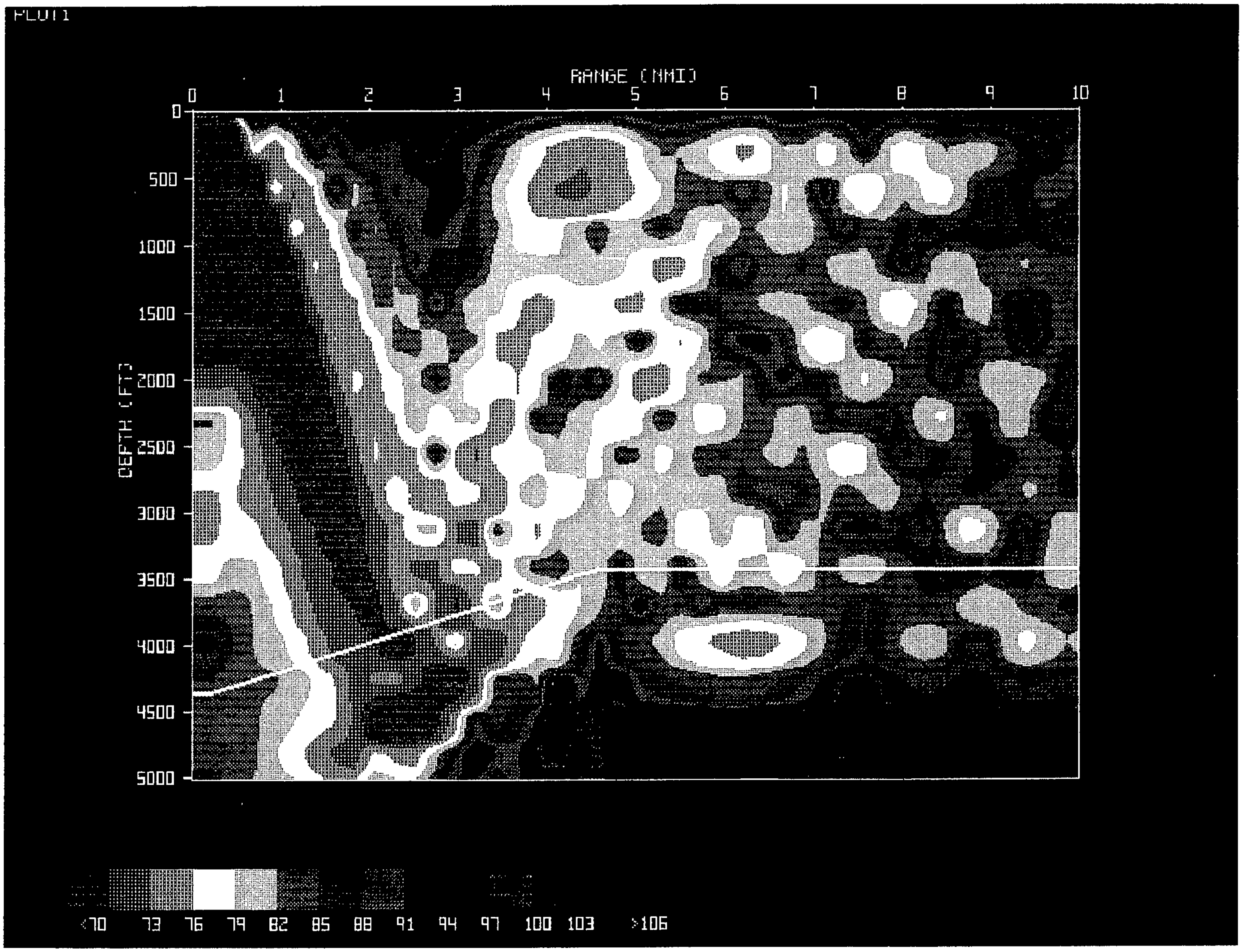

Figure 53. Modeled TL (whale to receive array) for 81.6° T radial, 17-Hz source at 100-ft depth, 181644Z August 1994.

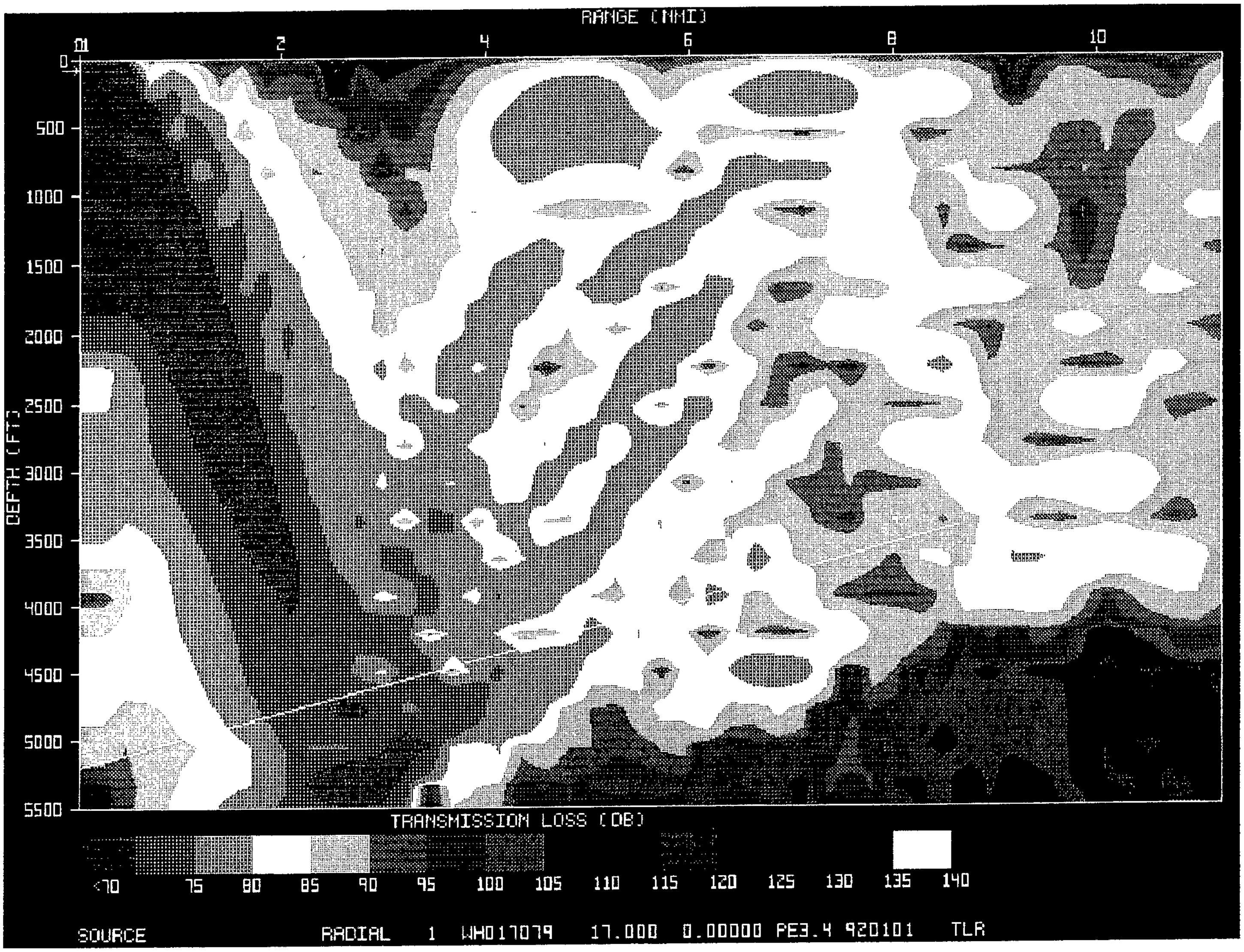

Figure 54. Modeled TL (whale to receive array) for 78.8° T radial, 17-Hz source at 100-ft depth, 181732Z August 1994.

Table 5. Blue whale 1 estimated source levels.

Time (zulu)	Bearing (deg)	Receive Level (dB//μPa @ 1m)	Estimated TL (dB)	Estimated Source Level (dB//μPa @ 1m)
1612	83	115	80	195
1644	81.6	112	80	192
1732	78.8	111	85	196

4. CONCLUSIONS

Received source levels of 70 to 85 dB below full transmit power did not appear to alter the vocalization patterns of the two blue whales studied. This conclusion was reached based on observations that the repetition rates, frequency characteristics, and durations of the whale vocalizations did not change during or just after an active transmission. In addition, blue whale 1 exhibited a well documented vocalization pattern consisting of alternating trills and chirps which compared favorably to the vocalization patterns of other blue whales recorded when an active source was not transmitting. This pattern, which consisted of five or six trill/chirp pairs with approximately 60-second breaks between them, followed by a longer nominal 160-second break was summarized in table 3.

Blue whales 1 and 2 were tracked intermittently over a 2.5-hour interval during which their range from the active source varied, but did not evidence a trend towards increasing range from the transmitting source. The ranges of both whales from the source at the start of the observation interval were not appreciably different from their ranges at the end. During this interval there were a total of 18 active transmissions or pings.

The inferences that can be made regarding the effects of active source transmissions on the blue whales studied are based on their acoustic responses (vocalization patterns) and their movement relative to the source. A literature search revealed more about blue whale vocalization patterns than their swimming habits (i.e. depth, speed, and course changes as well as dive and breathing intervals). To gain detailed information about their swimming behavior a tracking device would have to be placed on the whales themselves. In the absence of this data only general statements such as whether the whales opened or closed range with the acoustic source can be made. However, since breaks in their vocalization patterns are believed to be related to breathing pauses, some changes in their swimming habits can be inferred from alterations in their vocalization patterns.

In the final analysis the real question is what, if anything, can be concluded about the behavioral effect of low frequency sound on mysticetes (baleen whales) based on a limited analysis of blue whale vocalizations and a track of their movements relative to the acoustic source. A definitive answer requires both a better understanding of the "typical" behavior of the species of whale being studied and the effects of acoustic stimuli on the behavior of that whale species. It should be noted that the data for this report was not collected under controlled experimental conditions designed specifically to examine the effects of acoustic energy on marine mammals. Although none were noted in this analysis, other factors or stimuli that may affect changes in a whale's behavior can sometimes be present. Under these conditions it is more difficult (but not impossible) to determine whether changes in a whale's vocalization patterns are caused by a response to the acoustic source or to some other uncontrolled factor. All these considerations must be kept in mind and caution exercised when drawing any conclusions. With respect to all the Magellan II data analyzed for this report, of which the data discussed in section 3 was but a small representative sample, no evidence was found upon examination of blue whale vocalization patterns and tracks that would lead one to conclude that exposure to the stated acoustic levels had any near term behavioral effects. Any effects which repeated or long term exposure may have are beyond the scope of this report.

5. RECOMMENDATIONS

Further research as to the effects (both behavioral and physiological) of low-frequency sound on marine mammals is needed. To date, the threshold for sound levels that may possibly have adverse effects on marine mammals has not been determined. There is a need to determine this threshold, at least for the marine mammals typically encountered during LFA operations. Post-test analysis of the acoustic data recorded during LFA operations is an excellent means of accessing the potential behavioral impact of low-frequency sound on these marine mammals. A prime data set for further analysis is LFA-15 (Phase 1) during which there were multiple finback whale detections.

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APPENDIX A

Time-of-Arrival Difference Localization

TIME OF ARRIVAL DIFFERENCE LOCALIZATION

Using the correlation method one can determine the time-of-arrival difference of a discrete signal from a source to various acoustic sensors located on a line ("towed array") as shown in figure C-1. In figure C-1 the source is at position (x_s, y_s). Three acoustic sensors are shown at positions (x_i, y_i), (x_j, y_j) and (x_k, y_k). The origin of this coordinate system can be anywhere, but for this problem (x_i, y_i) is chosen as the origin.

In addition, for this problem it is assumed that all three sensors lie on the same straight line. That is, $y_i=y_j=y_k=0$. In a more general solution this would not be the case. In fact, in the typical solution, it may very well not be the case.

The time-of-arrival differences are given by:

$$t_{si} - t_{sj} = -\Delta t_{ij}$$
$$t_{si} - t_{sk} = -\Delta t_{ik}$$

where t_{sl} is the time for the discrete signal to travel from the source at (x_s, y_s) to one of the sensors at (x_l, y_l). If one assumes a constant sound speed (c) then the travel times become ranges:

$$ct_{si} - ct_{sj} = -c\Delta t_{ij}$$
$$ct_{si} - ct_{sk} = -c\Delta t_{ik}$$

which are written as

$$r_{si} - r_{sj} = -a_{ij}$$
$$r_{si} - r_{sk} = -a_{ik}$$

The locus of points satisfying these equations are, by definition, hyperbolas.

The equation of the hyperbolas can be derived from the law of cosines on a plane. The derivation for the hyperbola defined by a_{ij} follows:

$$r_{sj}^2 = r_{si}^2 + r_{ij}^2 - 2 r_{si} r_{ij} \cos(\theta_{si}),$$

but $r_{sj} = r_{si} + a_{ij}$

$\therefore$

$$\left(r_{si} + a_{ij}\right)^2 = r_{si}^2 + r_{ij}^2 - 2r_{si}r_{ij}\cos(\theta_{si})$$
$$r_{si}^2 + 2r_{si}a_{ij} + a_{ij}^2 = r_{si}^2 + r_{ij}^2 - 2r_{si}r_{ij}\cos(\theta_{si})$$
$$2r_{si}\left[r_{ij}\cos(\theta_{si}) + a_{ij}\right] = r_{ij}^2 - a_{ij}^2$$

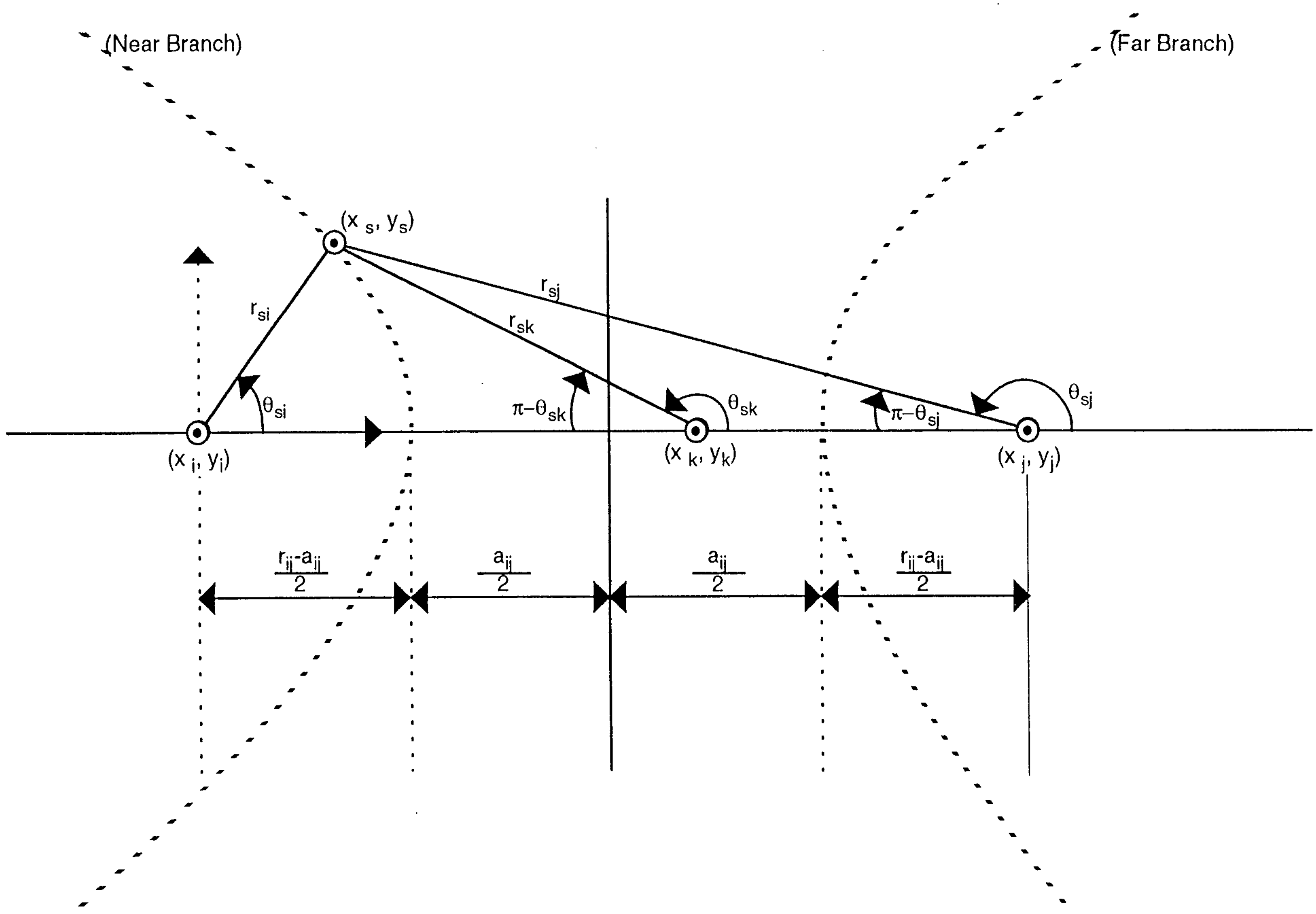

Figure A-1. Geometry for time-of-arrival difference localization problem.

$\therefore$

$$r_{si}(\theta_{si}) = \frac{r_{ij}^2 - a_{ij}^2}{2[r_{ij}\cos(\theta_{si}) + a_{ij}]},$$

where if $a_{ij} > 0$ then r_{si} (θ_{si}) lies on the near branch of the hyperbola as shown in figure C-1. If $a_{ij} < 0$ then r_{si} (θ_{si}) lies on the far branch of the hyperbola. In addition, for a hyperbola, the constraint $|a_{ij}| < r_{ij}$ must be satisfied (else an ellipse will be formed).

Note that:

$$r_{si}(0) = \frac{r_{ij}^2 - a_{ij}^2}{2(r_{ij} + a_{ij})}$$

$\therefore$

$$r_{si}(0) = \frac{r_{ij} - a_{ij}}{2}$$

From the assumed geometry one also has the hyperbola defined by a_{ik}:

$$r_{si}(\theta_{si}) = \frac{r_{ik}^2 - a_{ik}^2}{2[r_{ik}\cos(\theta_{si}) + a_{ik}]}$$

This means that the angle θ_{si} can be determined by:

$$\frac{r_{ij}^2 - a_{ij}^2}{2\left[r_{ij}\cos(\theta_{si}) + a_{ij}\right]} = \frac{r_{ik}^2 - a_{ik}^2}{2\left[r_{ik}\cos(\theta_{si}) + a_{ik}\right]}.$$

After some manipulation of terms one finds that:

$$\cos(\theta_{si}) = \frac{(r_{ij}^2 - a_{ij}^2)a_{ik} - (r_{ik}^2 - a_{ik}^2)a_{ij}}{(r_{ik}^2 - a_{ik}^2)r_{ij} - (r_{ij}^2 - a_{ij}^2)r_{ik}}$$

Given θ_{si} as determined above, one also can determine r_{si}.

Of course there will be error in the Δt_{sl} measurements and in assuming a value for c. Thus, there will be error in θ_{si} and r_{si}. In addition, the sensors being on a towed array will not generally lie on the same straight line.

For the RDA system the distance from the first sensor (which is the selected origin, i=1) to the n'th sensor is:

$$r_{i1} = (n-1)d,$$

where d is the spacing between the sensors.

This assumes the array is a straight line. In the more general case where the array is bent, the distance r_{ij} is not given by the above equation but will be somewhat smaller.

The geometry for the more general problem is shown in figure C-2. In this case the sensors (i, j and k) do not all lie on the same straight line.

The problem proceeds as before and one obtains:

$$r_{si}(\theta_{si}) = \frac{r_{ij}^2 - a_{ij}^2}{2(r_{ij}\cos(\theta_{si}) + a_{ij})}.$$

The other equation is a bit different, however, since

$$r_{sk}^2 = r_{si}^2 + r_{ik}^2 - 2r_{si}r_{ik}\cos(\theta_{si} + \theta_{ki})$$

$$\therefore$$

$$(r_{si} + a_{ik})^2 = r_{si}^2 + r_{ik}^2 - 2r_{si}r_{ik}\cos(\theta_{si} + \theta_{ki})$$

$$r_{si}^2 + 2r_{si}a_{ik} + a_{ik}^2 = r_{si}^2 + r_{ik}^2 - 2r_{si}r_{ik}\cos(\theta_{si} + \theta_{ki})$$

$$2r_{si}\left[r_{ik}\cos(\theta_{si} + \theta_{ki}) + a_{ik}\right] = r_{ik}^2 - a_{ik}^2, \quad or$$

$$r_{si}(\theta_{si}) = \frac{r_{ik}^2 - a_{ik}^2}{2\left[r_{ik}\cos(\theta_{si} + \theta_{ki}) + a_{ik}\right]}.$$

The angle θ_{ki} is known since (x_i, y_i), (x_j, y_j) and (x_k, y_k) are assumed known. That is,

$$r_{jk}^2 = r_{ij}^2 + r_{ik}^2 - 2r_{ij}r_{ik}\cos(\theta_{ki})$$

$$\theta_{ki} = Arc\cos\left[\frac{r_{ij}^2 + r_{ik}^2 - r_{jk}^2}{2r_{ij}r_{ik}}\right].$$

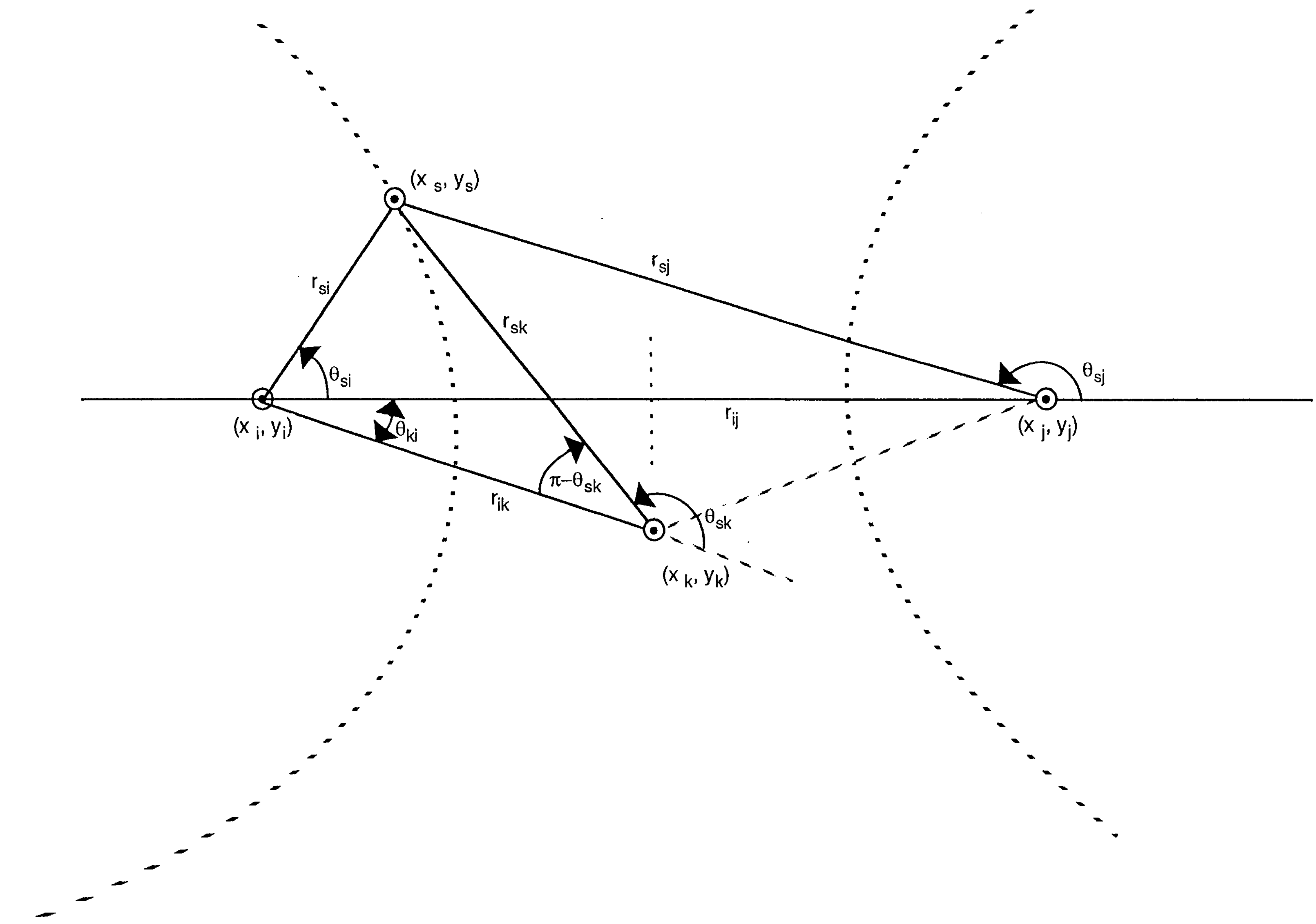

Figure A-2. General geometry for time-of-arrival difference localization.

A problem that remains is determining the sign of θ_{ki}. From the geometry shown in figure C-2, however, one sees that the sign of θ_{ki} is the opposite of the sign of y_k. If y_k is negative, then θ_{ki} is positive, and vice versa.

So by equating the two distinct equations for $r_{si}(\theta_{si})$ we can determine θ_{si}, but it is not as easy as before:

$$\frac{r_{ij}^{2}-a_{ij}^{2}}{2\left[r_{ij}\cos(\theta_{si})+a_{ij}\right]}=\frac{r_{ik}^{2}-a_{ik}^{2}}{2\left[r_{ik}\cos(\theta_{si}+\theta_{ki})+a_{ik}\right]}$$

$$\left(r_{ij}^{2}-a_{ij}^{2}\right)\left[r_{ik}\cos(\theta_{si}+\theta_{ki})+a_{ik}\right]=\left(r_{ik}^{2}-a_{ik}^{2}\right)\left[r_{ij}\cos(\theta_{si})+a_{ij}\right]$$

$$r_{ik}\left(r_{ij}^{2}-a_{ij}^{2}\right)\cos(\theta_{si}+\theta_{ki})+a_{ik}\left(r_{ij}^{2}-a_{ij}^{2}\right)=r_{ij}\left(r_{ik}^{2}-a_{ik}^{2}\right)\cos(\theta_{si})+a_{ij}\left(r_{ik}^{2}-a_{ik}^{2}\right)$$

$$r_{ik}\left(r_{ij}^{2}-a_{ij}^{2}\right)\cos(\theta_{si})\cos(\theta_{ki})-r_{ik}\left(r_{ij}^{2}-a_{ij}^{2}\right)\sin(\theta_{si})\sin(\theta_{ki})-r_{ij}\left(r_{ik}^{2}-a_{ik}^{2}\right)\cos(\theta_{si})$$
$$=a_{ij}\left(r_{ik}^{2}-a_{ik}^{2}\right)-a_{ik}\left(r_{ij}^{2}-a_{ij}^{2}\right)$$

$\therefore$

$$\left[r_{ik}\left(r_{ij}^{2}-a_{ij}^{2}\right)\cos(\theta_{ki})-r_{ij}\left(r_{ik}^{2}-a_{ik}^{2}\right)\right]\cos(\theta_{si})-\left[r_{ik}\left(r_{ij}^{2}-a_{ij}^{2}\right)sin(\theta_{ki})\right]\sin(\theta_{si})$$
$$=a_{ij}\left(r_{ik}^{2}-a_{ik}^{2}\right)-a_{ik}\left(r_{ij}^{2}-a_{ij}^{2}\right).$$

This equation is written as:

$$k_3\cos(\theta_{si})-k_2\sin(\theta_{si})=k_1$$

$$k_1=a_{ij}\left(r_{ik}^{2}-a_{ik}^{2}\right)-a_{ik}\left(r_{ij}^{2}-a_{ij}^{2}\right)$$

$$k_2=r_{ik}\left(r_{ij}^{2}-a_{ij}^{2}\right)\sin(\theta_{ki})$$

$$k_3=r_{ik}\left(r_{ij}^{2}-a_{ij}^{2}\right)\cos(\theta_{ki})-r_{ij}\left(r_{ik}^{2}-a_{ik}^{2}\right).$$

To solve this problem, one sets:

$$\text{A}\cos\left(\theta_{si}+\Psi\right)=k_1,\ \text{or}$$

$$\text{A}\cos\left(\Psi\right)\cos\left(\theta_{si}\right)-\text{A}\sin\left(\Psi\right)\sin\left(\theta_{si}\right)=k_1$$

$\therefore$

$$A \cos(\Psi) = k_3$$

$$A \sin(\Psi) = k_2$$

$$A = \pm\left(k_2^{\,2} + k_3^{\,2}\right)^{1/2}$$

$$\Psi = \text{Arctan}\left(\frac{k_2}{k_3}\right), \quad k_3 \neq 0.$$

If $k_3 = 0$, then

$$\theta_{si} = \text{Arcsin}\left(-\frac{k_1}{k_2}\right), \quad k_2 \neq 0.$$

If $k_3 \neq 0$, then

$$\theta_{si} = \text{Arccos}\left[\frac{k_1}{\pm\left(k_2^{\,2} + k_3^{\,2}\right)^{1/2}}\right] - \text{Arctan}\left(\frac{k_2}{k_3}\right)$$

Given θ_{si}, the bearing to the source from sensor i, one can now determine the range to the source from sensor i (r_{si}).

APPENDIX B

RANGE TO A SOUND SOURCE GIVEN BEARINGS FROM TWO SENSORS

The geometry for this problem is shown in figure B-1. The sensors in this case are two small hydrophone arrays towed behind a ship. The two arrays towed by a single line are separated a distance "d" apart as indicated in figure B-1. Each array consists of 48 hydrophones. Beamforming can be done so that a bearing to a sound source is available from each array. The range to the sound source can then be determined from the geometry shown in figure B-1.

It is assumed for the moment, that the average headings of the two arrays (H_f and H_a) are identical as indicated in figure B-1.

The constraint for a cross-fix on the acoustic source is that,

$B_a > B_f$,

otherwise the two bearing lines will not intersect.

Since the geometry is symmetric about the the line joining the two arrays, the bearings on the other side of the array are equally valid (2π-B_f and 2π-B_a relative to the figure B-1 geometry).

Given the two bearings and the above conditions, one finds the range from the cosine law for plane geometry. That is:

$$
\begin{aligned}
r_f &= d\cos(B_f) + r_a\cos(B_a - B_f), \\
r_a &= r_f\cos(B_a - B_f) + d\cos(\pi - B_a) \\
&= r_f\cos(B_a - B_f) - d\cos(B_a)
\end{aligned}
$$

Thus the ranges are given by:

$$r_a = d\frac{\cos(B_f)\cos(B_a - B_f) - \cos(B_a)}{\sin^2(B_a - B_f)}$$

$$r_f = d\frac{\cos(B_f) - \cos(B_a)\cos(B_a - B_f)}{\sin^2(B_a - B_f)}.$$

A problem that occurs is that the headings of the arrays may be rotated slightly with respect to one another as shown in figure B-2. This rotation will result in errors in the computed ranges since the geometry of figure B-1 assumes the headings line up along the line joining the two arrays. The way to avoid this problem is to line up the average headings of each array to the same heading reference (H_{ref}). For H_{ref} we take as the average of all the heading sensor data. There are two heading sensors on the forward array and three on the aft array. The heading of the arrays are lined up to H_{ref} by rotating each by an amount (H_{ref} - H_f) degrees for the forward array and (H_{ref} - H_a) degrees for the aft array. The critical part is lining up each array to H_{ref} even if H_{ref} itself is skewed relative to the line joining the two arrays. If (H_{ref} - H_f)>0, then one rotates the forward array beam bearings to the right (toward increasing bearings) by (H_{ref} - H_f). If (H_{ref} - H_f)<0, then one rotates the forward array beam bearings to the left (toward decreasing bearings) by (H_f -H_{ref}).

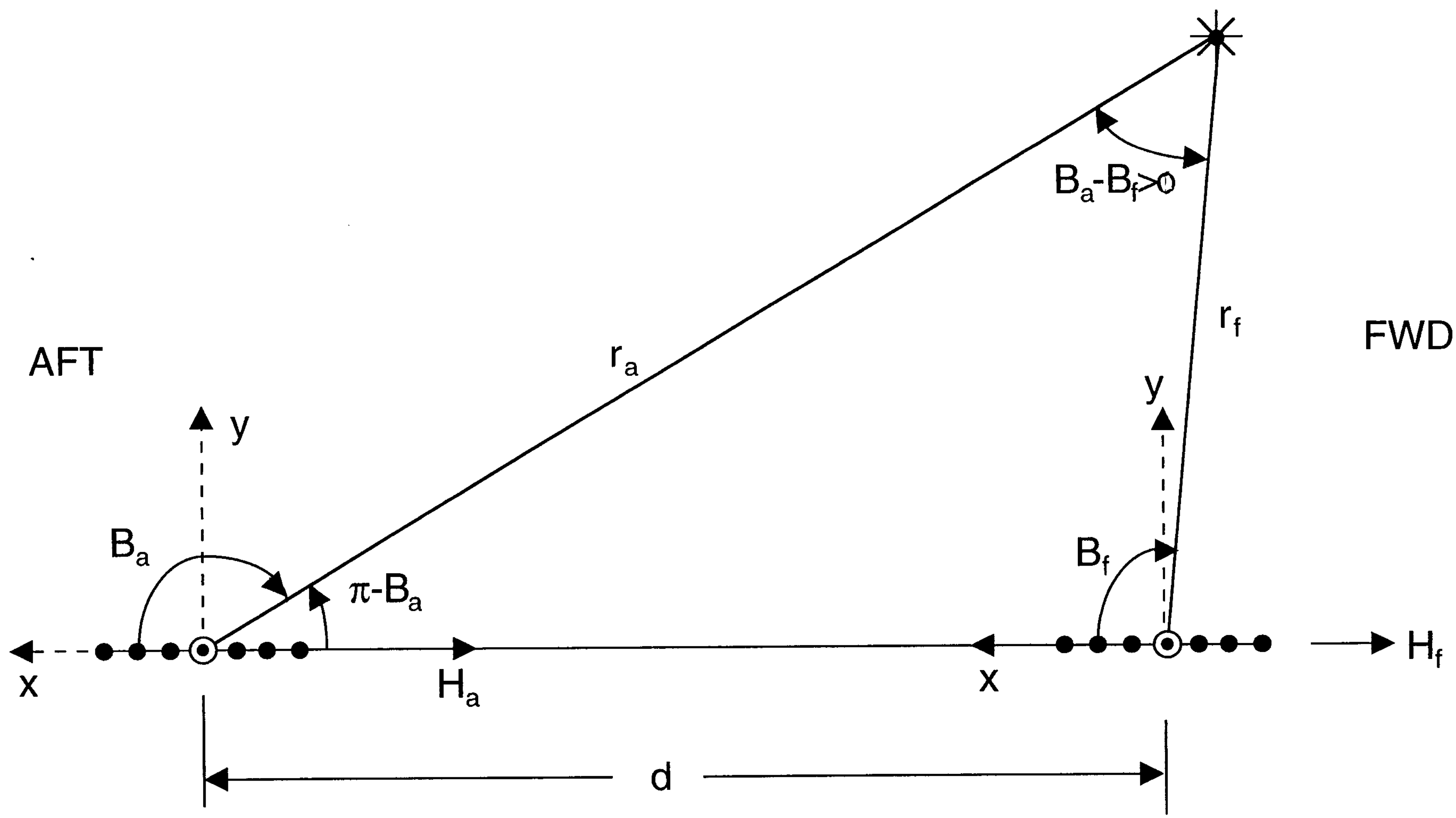

Figure B-1. Geometry for determining range using subarrays.

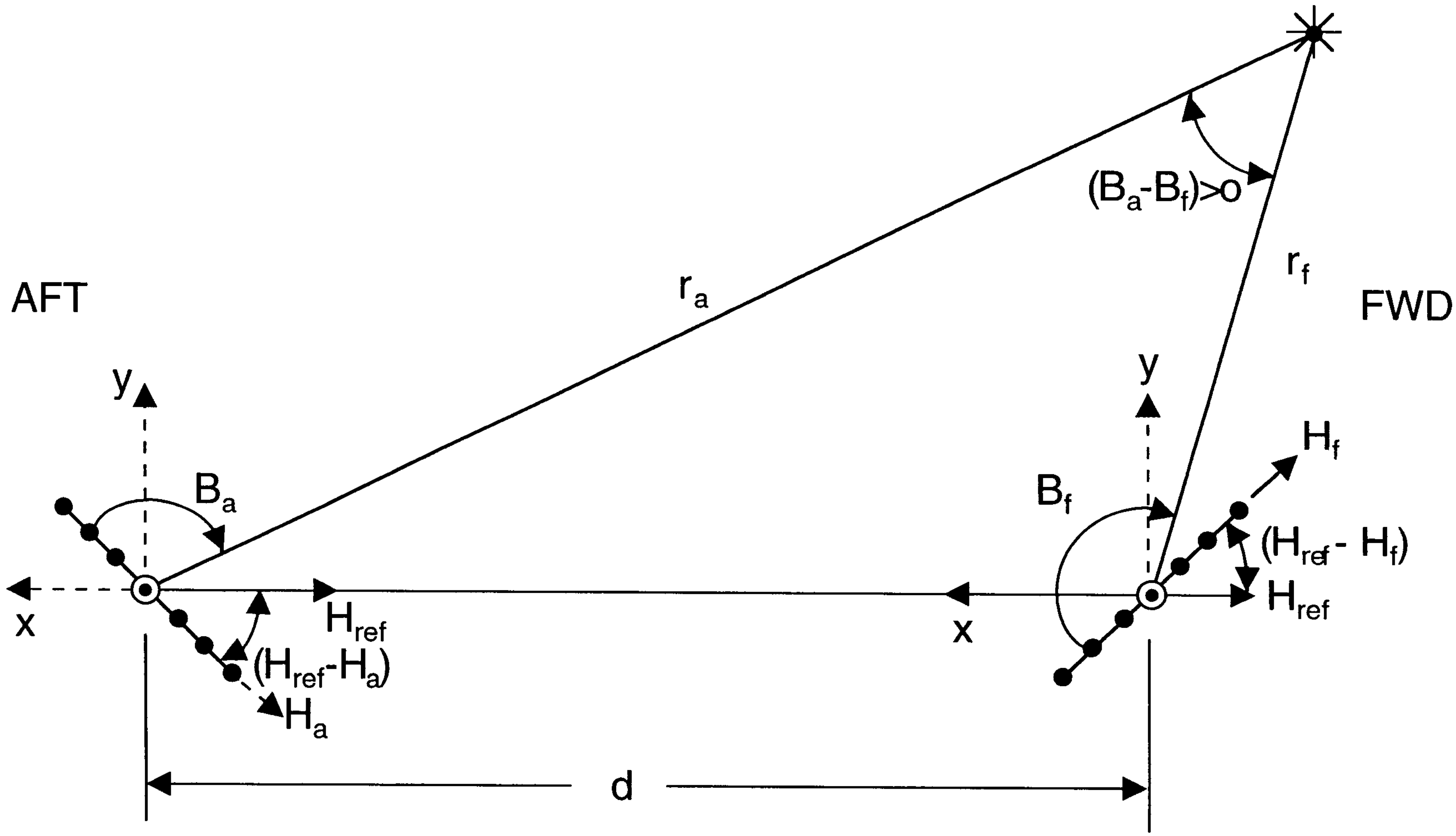

Figure B-2. Geometry for determining range with subarrays rotated.

APPENDIX C

Subset of Exabyte (8mm) Tapes Selected for Analysis

C.1 SUBSET OF EXABYTE (8MM) TAPES SELECTED FOR ANALYSIS

TAPE #	DTG DDHHMMZ MMM YYYY	COMMENT
S001	181723Z Aug 1994	Segment 1. Blue whales.
S002	---	Segment 1. " "
S003	181852Z Aug 1994	Segment 1. Blue whales.
S004	---	Segment 1. " "
S005	262228Z Jul 1994	Shakedown.
S006	---	Shakedown.
S007	262357Z Jul 1994	Shakedown.
S008	---	Shakedown.
S009	270126Z Jul 1994	Shakedown.
S010	---	Shakedown.
S011	---	Shakedown.
S012	270721Z Jul 1994	Shakedown.
S013	---	Shakedown.
S014	270850Z Jul 1994	Shakedown.
S015	---	Shakedown.
S016	181554Z Aug 1994	Segment 1. Blue whales. One loud.
S017	---	Segment 1. " "
S018	051729Z Aug 1994	Segment 1. Blue whales.
S019	---	Segment 1. " "
S020	052227Z Aug 1994	Segment 1. Distant blue whales.
S021	---	Segment 1. " "
S022	052058Z Aug 1994	Segment 1. Distant blue whales.
S023	---	Segment 1. " "
S024	152341Z Aug 1994	Segment 1. Strong Blue whale vocalizations.
S025	---	Segment 1. " "
S026	160109Z Aug 1994	Segment 1. " "
S027	---	Segment 1. " "
S028	160238Z Aug 1994	Segment 1. " "
S029	---	Segment 1. " "
S030	250956Z Aug 1994	Segment 2. Several Finbacks Present.
S031	---	Segment 2. Started array turn at 1050Z.
S032	251125Z Aug 1994	Segment 2. Array turn complete at 1145Z.
S033	---	Segment 2. Finbacks close to ship 1204Z.
S034	251254Z Aug 1994	Segment 2. Stop XMIT 1210Z.Resume 1230Z.
S035	---	Segment 2. Finbacks move to AFT ENDFIRE.
S036	280734Z Aug 1994	Segment 2. ???
S037	---	Segment 2. ???
S038	280903Z Aug 1994	Segment 2. Finbacks distant.
S039	---	Segment 2. Fin close to ship: 1015Z.
S040	281032Z Aug 1994	Segment 2. Fin strong vocalizations.
S041	---	Segment 2. Good fin contacts.
S042	281756Z Aug 1994	Segment 2. Many good fin contacts.
S043	---	Segment 2. " "
S044	281925Z Aug 1994	Segment 2. Close in fin contacts.
S045	---	Segment 2. " "
S046	282054Z Aug 1994	Segment 2. Many finback contacts.
S047	---	Segment 2. " "
S048	290250Z Aug 1994	Segment 2. High level finback contact.
S049	---	Segment 2. " "
S050	290419Z Aug 1994	Segment 2. Finback.
S051	---	Segment 2. " "
S052	290547Z Aug 1994	Segment 2. Finback.
S053	---	Segment 2. " "

S054	302019Z Aug 1994	Segment 2. Finbacks distant or quiet now.
S055	---	Segment 2. ""
S056	302147Z Aug 1994	Segment 2. ""
S057	---	Segment 2. ""
S058	302316Z Aug 1994	Segment 2. High level signals (Marine Mammal?)
S059	---	Segment 2. ""
S060	011814Z Sep 1994	Segment 2. Undersea Earthquake.
S061	---	Segment 2. Aftershocks.
S062	011943Z Sep 1994	Segment 2. All quiet.
S063	---	Segment 2. ""
S064	012112Z Sep 1994	Segment 2. ""
S065	---	Segment 2. ""
S066	012241Z Sep 1994	Segment 2. ""
S067	---	Segment 2. ""

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The effects of low-frequency sound on marine mammals (particularly the baleen whales) are not well understood. Although baleen whales are known to produce low-frequency sounds, very little is known about their auditory sensitivity. This analysis studied the behavior of blue whales in the vicinity of a loud, low-frequency source by evaluating an available data set recorded during a Low Frequency Active (LFA) experiment. the received source levels at the whales were estimated from the known source levels and a Parabolic Equation (PE) propagation model.

Element level acoustic data collected with a high-gain towed array during the Magellan II sea test conducted off the coast of California contained blue and finback whales was spectrally processed to determine the frequency content and repetition rates of their vocalizations. Subarray beamforming was used to cross-fix the whale positions and track their movement relative to the active source. The effects of active source transmissions on blue whale vocalization patterns and on their movement relative to the source were analyzed.

ABSTRACT CONTINUED ON NEXT PAGE . . .

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Estimated received source levels at the whales of 70 to 85 dB below full transmit power did not appear to alter the vocalization patterns of the blue whales as determined by analysis of the repetition rates, frequency characteristics, and durations of the whale vocalizations before, during, and after active transmissions. In addition, several blue whales exhibited a well-documented vocalization pattern consisting of alternating trills and chirps that compared favorably to the vocalization patterns of other blue whales recorded when an active source was not transmitting. Two blue whales were tracked intermittently over a 2.5-hour interval during which there were 18 active transmissions or pings. The ranges of both whales from the source varied during this interval but did not show a tendency towards increasing range from the source over time. Further research as to the effects (both behavioral and physiological) of acoustic energy on marine mammals is needed. This research would enable a sound-level threshold for marine mammals to be determined in the frequency band of interest.

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